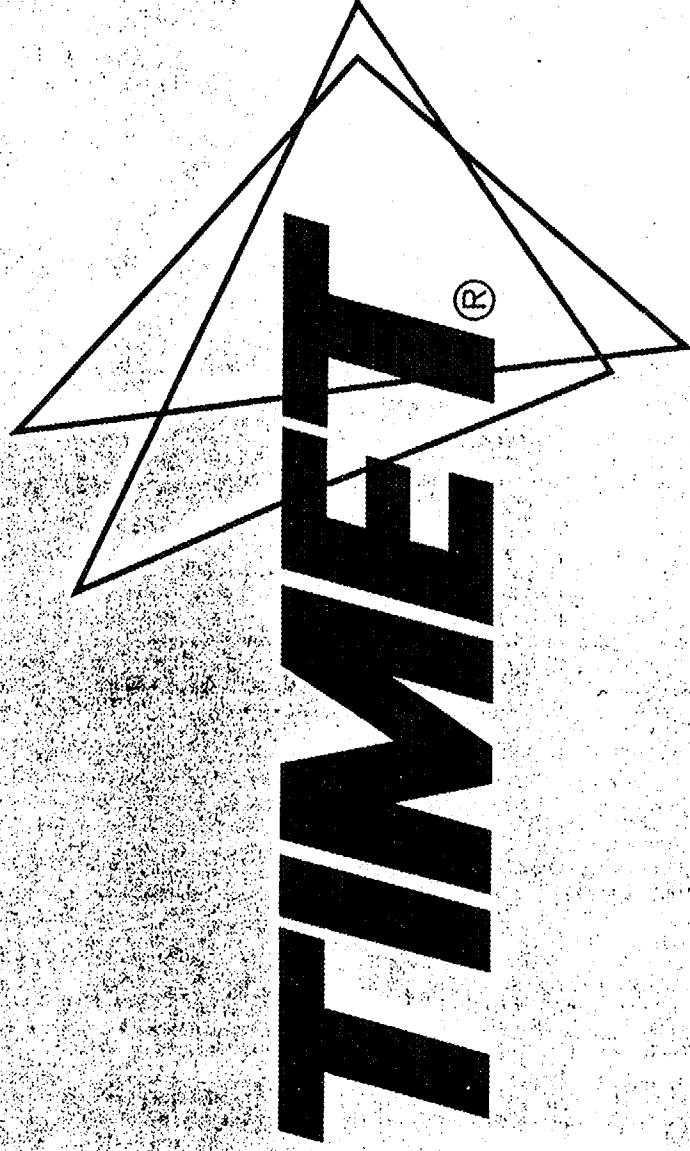


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Corrosion Resistance of Titanium



First in Titanium Worldwide

Forward

Since titanium metal first became a commercial reality in 1950, corrosion resistance has been an important consideration in its selection as an engineering structural material. Titanium has gained acceptance in many media where its corrosion resistance and engineering properties have provided the corrosion and design engineer with a reliable and economic material.

This brochure summarizes the corrosion resistance data accumulated in over forty years laboratory testing and application experience. The corrosion data were obtained using generally acceptable testing methods; however, since service conditions may be dissimilar, TIMET recommends testing under the actual anticipated operating conditions.

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TIMET 40 YEAR WARRANTY

In most power plant surface condenser tubing, tubesheet and service water pipe applications, TIMET CODEWELD® Tubing and CODEROLL® Sheet, Strip and Plate can be covered by written warranties against failure by corrosion for a period of 40 years.

For additional information and copies of these warranties, please contact any of the TIMET locations shown on the back cover of this brochure.

The data and other information contained herein are derived from a variety of sources which TIMET believes are reliable. Because it is not possible to anticipate specific uses and operating conditions, TIMET urges you to consult with our technical service personnel on your particular applications. A copy of TIMET's warranty is available on request.

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Titanium and this paper are recycled.

Introduction

Many titanium alloys have been developed for aerospace applications where mechanical properties are the primary consideration. In industrial applications, however, corrosion resistance is the most important property.

The commercially pure (c.p.) and alloy grades typically used in industrial service are listed in Table 1. Discussion of corrosion resistance in this brochure will be limited to these alloys.

In the following sections, the resistance of titanium to specific environments is discussed followed by an explanation of the types of corrosion that can affect titanium. The principles outlined and the data given should be used, with caution, as a guide for the application of titanium. In many cases, data were obtained in the laboratory. Actual in-plant environments often contain impurities which can exert their own effects. Heat transfer conditions or unanticipated deposited residues can also alter results. Such factors may require in-plant corrosion tests. Corrosion coupons are available from TIMET for laboratory or in-plant testing programs. A tabulation of available general corrosion data is given in the Appendix.

Titanium offers outstanding resistance to a wide variety of environments. In general, **TIMETAL® Code-12** and **50A Pd** extend the usefulness of unalloyed titanium to more severe conditions. **TIMETAL® 6-4**, on the other hand, has somewhat less resistance than unalloyed titanium, but is still outstanding in many environments compared to other structural metals.

Titanium and its alloys provide excellent resistance to general and localized attack under most oxidizing, neutral and inhibited

reducing conditions. They also remain passive under mildly reducing conditions, although they may be attacked by strongly reducing or complexing media.

Titanium metal's corrosion resistance is due to a stable, protective, strongly adherent oxide film. This film forms instantly when a fresh surface is exposed to air or moisture. According to Andreeva⁽¹⁾ the oxide film formed on titanium at room temperature immediately after a clean surface is exposed to air is 12–16 Å thick. After 70 days it is about 50 Å. It continues to grow slowly reaching a thickness of 80–90 Å in 545 days and 250 Å in four years. The film growth is accelerated under strongly oxidizing conditions, such as heating in air, anodic polarization in an electrolyte or exposure to oxidizing agents such as HNO₃, CrO₃, etc.

The composition of this film varies from TiO₂ at the surface, to Ti₂O₃, to TiO at the metal interface⁽²⁾. Oxidizing conditions promote the formation of TiO₂ so that in such environments the film is primarily TiO₂. This film is transparent in its normal thin configuration and not detectable by visual means.

A study of the corrosion resistance of titanium is basically a study of the properties of the oxide film. The oxide film on titanium is very stable and is only attacked by a few substances, most notably, hydrofluoric acid. Titanium is capable of healing this film almost instantly in any environment where a trace of moisture or oxygen is present because of its strong affinity for oxygen.

Anhydrous conditions in the absence of a source of oxygen should be avoided since the protective film may not be regenerated if damaged.

Table 1 – Titanium Alloys Commonly Used in Industry

TIMET Designation TIMETAL®	ASTM Grade	Ultimate Tensile Strength (min.)	Yield Strength (min.) 0.2% Offset	Nominal Composition
35A	1	35,000 psi	25,000 psi	C.P. Titanium*
50A	2	50,000 psi	40,000 psi	C.P. Titanium*
65A	3	65,000 psi	55,000 psi	C.P. Titanium*
75A	4	80,000 psi	70,000 psi	C.P. Titanium*
6-4	5	130,000 psi	120,000 psi	6% Al, 4% V
50A Pd-	7	50,000 psi	40,000 psi	0.15% Pd
Code-12	12	70,000 psi	50,000 psi	0.3% Mo, 0.8% Ni
3-2.5	9	90,000 psi	75,000 psi	3.0% Al, 2.5% V

* Commercially Pure (Unalloyed) Titanium

Chlorine, Chlorine Chemicals and Chlorides

Chlorine and chlorine compounds in aqueous solution are not corrosive toward titanium because of their strongly oxidizing natures. Titanium is unique among metals in handling these environments.

The corrosion resistance of titanium to moist chlorine gas and chloride-containing solutions is the basis for the largest number of titanium applications. Titanium is widely used in chlor-alkali cells; dimensionally stable anodes; bleaching equipment for pulp and paper; heat exchangers, pumps, piping and vessels used in the production of organic intermediates; pollution control devices; and even for human body prosthetic devices.

The equipment manufacturer or user faced with a chlorine or chloride corrosion problem will find titanium's resistance over a wide range of temperatures and concentrations particularly useful.

Chlorine Gas

Titanium is widely used to handle moist chlorine gas and has earned a reputation for outstanding performance in this service. The strongly oxidizing nature of moist chlorine passivates titanium resulting in low corrosion rates in moist chlorine.

Dry chlorine can cause rapid attack on titanium and may even cause ignition if moisture content is sufficiently low (Table 2)⁽³⁾. However, one percent of water is generally sufficient for passivation or repassivation after mechanical damage to titanium in chlo-

rine gas under static conditions at room temperature (Figure 1)⁽⁴⁾. Factors such as gas pressure, gas flow, and temperature as well as mechanical damage to the oxide film on the titanium, influence the actual amount of moisture required. Approximately 1.5 percent moisture is apparently required for passivation at 390°F (199°C).⁽³⁾ *Caution should be exercised when employing titanium in chlorine gas where moisture content is low.*

Chlorine Chemicals

Titanium is fully resistant to solutions of chlorites, hypochlorites, chlorates, perchlorates and chlorine dioxide. Titanium equipment has been used to handle these chemicals in the pulp and paper industry for many years with no evidence of corrosion.⁽⁵⁾ Titanium is used today in nearly every piece of equipment handling wet chlorine or chlorine chemicals in a modern bleach plant, such as chlorine dioxide mixers, piping, and washers. In the future it is expected that these applications will expand, including use of titanium in equipment for ClO₂ generators and waste water recovery.

Chlorides

Titanium has excellent resistance to corrosion by neutral chloride solutions even at relatively high temperatures (Table 3). Titanium generally exhibits very low corrosion rates in chloride environments.

Table 2 – Resistance of Titanium to Chlorine

Environment	Temperature °F(°C)	Corrosion Rate – mpy (mm/y)	
		TIMETAL® 50A	TIMETAL® Code-12
Wet Chlorine	50-190 (10-88)	Nil-0.02 (0.001)	—
Water Saturated, Chlorine Cell Gas	190 (88)	0.065* (0.002)	0.035* (0.001)
Dry Chlorine	86 (30)	Rapid Attack, Ignition	—

* Welded Samples

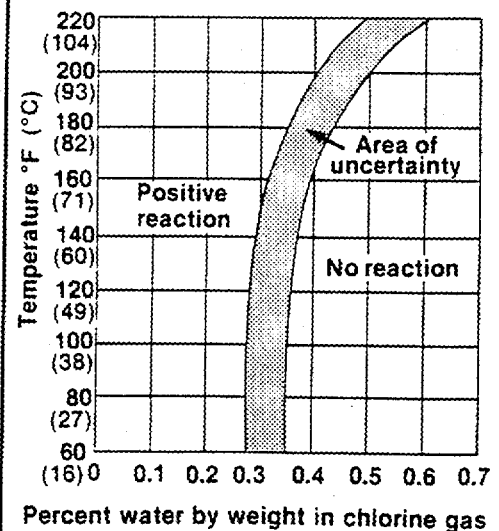


Figure 1 – Preliminary Data Reflecting Percent Water Content Necessary to Passivate Unalloyed in Titanium Chlorine Gas.

Table 3 – Resistance of Unalloyed Titanium To Corrosion by Aerated Chloride Solutions¹⁷⁷

Chloride	Concentration %	Temperature F (°C)	Corrosion Rate mpy (mm/y)
Aluminum chloride	5-10	140 (60)	0.12 (0.003)
	10	212 (100)	0.09 (0.002)
	10	302 (150)	1.3 (0.033)
	20	300 (149)	630 (16.0)
	25	68 (20)	0.04 (0.001)
	25	212 (100)	258 (6.55)
	40	250 (121)	4300 (109.2)
Ammonium chloride	All	68-212 (20-100)	<0.5 (<0.013)
Barium chloride	5-25	212 (100)	<0.01 (<0.000)
Calcium chloride	5	212 (100)	0.02 (0.001)
	10	212 (100)	0.3 (0.008)
	20	212 (100)	0.6 (0.015)
	55	220 (104)	0.02 (0.001)
	60	300 (149)	<0.01 (<0.000)
	62	310 (154)	2-16 (0.051-0.406)
	73	350 (177)	84 (2.13)
Cupric chloride	1-20	212 (100)	<0.5 (<0.013)
	40	Boiling	0.2 (0.005)
Cuprous chloride	50	194 (90)	<0.1 (<0.003)
Ferric chloride	1-20	70 (21)	Nil
	1-40	Boiling	<0.5 (<0.013)
	50	Boiling	0.16 (0.004)
	50	302 (150)	<0.7 (<0.018)
Lithium chloride	50	300 (149)	Nil
Magnesium chloride	5	212 (100)	0.03 (0.001)
	20	212 (100)	0.4 (0.010)
	50	390 (199)	0.2 (0.005)
Manganous chloride	5-20	212 (100)	Nil
Mercuric chloride	1	212 (100)	0.01 (0.000)
	5	212 (100)	0.42 (0.011)
	10	212 (100)	0.04 (0.001)
	55	215 (102)	Nil
Nickel chloride	5-20	212 (100)	0.14 (0.004)
Potassium chloride	Saturated	70 (21)	Nil
	Saturated	140 (60)	<0.01 (<0.000)
Stannic chloride	5	212 (100)	0.12 (0.003)
Stannous chloride	Saturated	70 (21)	Nil
Sodium chloride	3	Boiling	0.01 (0.000)
	20	165 (74)	0.01 (0.000)
	29	230 (110)	0.1 (0.003)
	Saturated	70 (21)	Nil
	Saturated	Boiling	Nil
Zinc chloride	20	220 (104)	Nil
	50	302 (150)	Nil
	75	392 (200)	24 (0.610)
	80	392 (200)	8000 (203.2)

The limiting factor for application of titanium and its alloys to aqueous chloride environments appears to be crevice corrosion. When crevices are present, unalloyed titanium will sometimes corrode under conditions not predicted by general corrosion rates (See Crevice Corrosion). TIMET studies have shown that pH and temperature are important variables with regard to crevice corrosion in brines.

The temperature-pH relationship defines crevice corrosion susceptibility for **TIMETAL® 50A**, **Code-12**, and **50A Pd** in saturated sodium chloride brines (Figures 2, 3, and 4). Corrosion in sharp crevices in near neutral brine is possible with unalloyed titanium at about 200°F (93°C) and above (Figure 2). Lowering the pH of the brine lowers the temperature at which crevice corrosion is likely, whereas raising the pH reduces crevice corrosion susceptibility. However, crevice corrosion on titanium is not likely to occur below 158°F (70°C). The presence of high concentrations of cations other than sodium such as Ca^{+2} or Mg^{+2} , can also alter this relationship and cause localized corrosion at lower temperatures than those indicated in the diagrams.

TIMETAL® Code-12 and **50A Pd** offer considerably improved resistance to crevice corrosion compared to unalloyed titanium (Figures 3 and 4). These alloys have not shown any indication of any kind of corrosion in laboratory tests in neutral saturated brines to temperatures in excess of 600°F (316°C). **TIMETAL® Code-12** maintains excellent resistance to crevice corrosion down to pH values of about 3. Below pH 3, **TIMETAL® 50A Pd** offers distinctly better resistance than **TIMETAL® Code-12**. **TIMETAL® Code-12** or **50A Pd** will resist crevice corrosion in boiling, low pH salt solutions which corrode **TIMETAL® 50A** (Table 4).

Bromine, Iodine and Fluorine

The resistance of titanium to bromine and iodines is similar to its resistance to chlorine. It is attacked by the dry gas but is passivated by the presence of moisture. Titanium is reported to be resistant to bromine water.⁽⁴⁾

Titanium is not recommended for use in contact with fluorine gas. The possibility of formation of hydrofluoric acid even in minute quantities can lead to very high corrosion rates. Similarly, the presence of free fluorides in acid aqueous environments can lead to formation of hydrofluoric acid and, consequently, rapid attack on titanium. On the other hand, fluorides chemically bound or fully complexed by metal ions, or highly stable fluorne containing compounds (e.g., fluorocarbons), are generally non-corrosive to titanium.

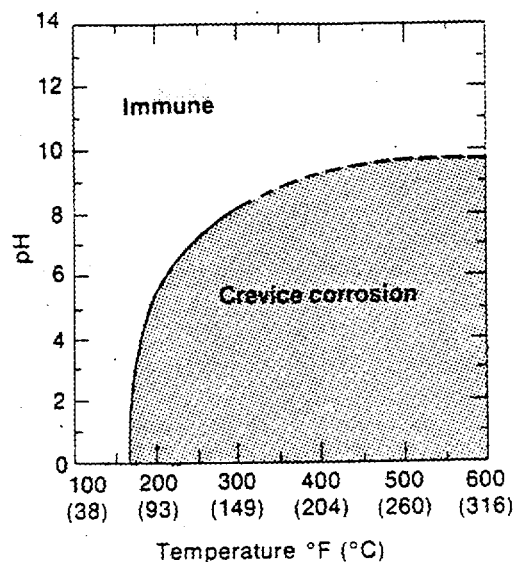


Figure 2 – Effect of Temperature and pH on Crevice Corrosion of Unalloyed Titanium (**TIMETAL® 50A**) in Saturated NaCl Brine

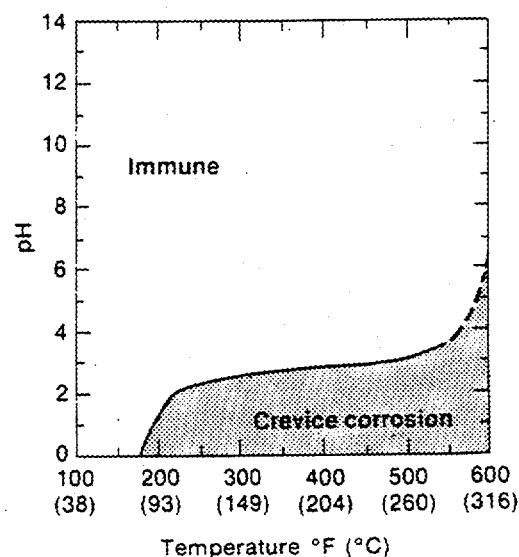


Figure 3 – Effect of Temperature and pH on Crevice Corrosion of **TIMETAL® Code-12** in Saturated NaCl Brine

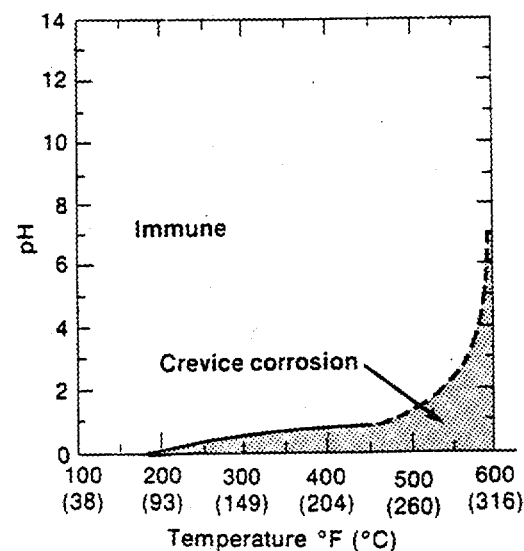


Figure 4 – Effect of Temperature and pH on Crevice Corrosion of **TIMETAL® 50A Pd** in Saturated NaCl Brine

Table 4 – Resistance of Titanium to Crevice Corrosion in Boiling Solutions

Environment	pH	500 hour test results		
		TIMETAL® 50A	TIMETAL® Code-12	TIMETAL® 50A Pd
ZnCl ₂ (saturated)	3.0	F	R	R
10% AlCl ₃	—	F	R	R
42% MgCl ₂	4.2	F	R	R
10% NH ₄ Cl	4.1	F	R	R
NaCl (saturated)	3.0	F	R	R
NaCl (saturated) + Cl ₂	2.0	F	F	R
10% Na ₂ SO ₄	2.0	F	R	R
10% FeCl ₃	0.6	F	F	R

Metal-to-Teflon crevice samples used.

F Failed (samples showed corrosion in metal-to-Teflon crevices).

R Resisted (samples showed no evidence of corrosion).

Table 5 – Corrosion of Titanium in Ambient Seawater

Alloy	Ocean Depth ft (m)	Corrosion Rate mpy (mm/y)		Reference
Unalloyed titanium	Shallow	3.15×10^{-5}	(0.8×10^{-6})	(10)
	2,362-6,790 (720-2070)	<0.010	(<0.00025)	(9)
	4,264-4,494 (1300-1370)	<0.010	(<0.00025)	(9)
	5-6,790 (1.5-2070)		(0.0)	(9)
	5,642 (1720)	0.002	(0.00004)	(12)
TIMETAL® 6-4	5-6,790 (1.5-2070)	<0.010	(<0.00025)	(9)
	5,642 (1720)	3.15×10^{-5}	(8×10^{-6})	(12)
	5,642 (1720)	≤0.039	(≤0/001)	(13)

**Table 6 – Effect of Seawater Velocity
on Erosion of Unalloyed Titanium
and TIMETAL® 6-4**

Seawater Velocity ft/sec (m/sec)	Erosion Rate – mpy (mm/y)	
	Unalloyed Titanium	TIMETAL® 6-4
0-2 (0-0.61)	Nil	—
25 (7.6)	Nil	—
120 (36.6)	0.3 (0.008)	0.4 (0.010)

Resistance to Waters

Fresh Water – Steam

Titanium resists all forms of corrosive attack by fresh water and steam to temperatures in excess of 600°F (316°C).¹⁷ The corrosion rate is very low or a slight weight gain is experienced. Titanium surfaces are likely to acquire a tarnished appearance in hot water or steam but will be free of corrosion.

Some natural river waters contain manganese which deposits as manganese dioxide on heat exchanger surfaces. Chlorination treatments used to control sliming results in severe pitting and crevice corrosion on stainless steel surfaces. Titanium is immune to this form of corrosion and is an ideal material for handling all natural waters.

Seawater

General Corrosion

Titanium resists corrosion by seawater to temperatures as high as 500°F (260°C). Titanium tubing, exposed for 16 years to polluted seawater in a surface condenser, was slightly discolored but showed no evidence of corrosion.¹⁸ Titanium has provided nearly twenty years of trouble-free seawater service for the chemical, oil refining and desalination industries.

Exposure of titanium for many years to depths of over a mile below the ocean surface has not produced any measurable corrosion¹⁹ (Table 5). Pitting and crevice corrosion are totally absent, even if marine deposits form. The presence of sulfides in seawater does not affect the resistance of titanium to corrosion. Exposure of titanium to marine atmospheres or splash or tide zone does not cause corrosion.^{10 11 12 13}

Erosion

Titanium has the ability to resist erosion by high velocity seawater (Table 6). Velocities as high as 120 ft./sec. cause only a minimal rise in erosion rate.¹⁴ The presence of abrasive particles, such as sand, has only a small effect on the corrosion resistance of titanium under conditions that are extremely detrimental to copper and aluminum base alloys.

Table 7 – Erosion of Unalloyed Titanium in Seawater Containing Suspended Solids⁽¹⁵⁾

Flow Rate ft/sec (m/sec)	Suspended Matter In Seawater	Duration Hrs.	Corrosion/Erosion – mpy (mm/y)		
			TIMETAL® 50A	70 Cu-30 Ni*	Aluminum Brass
23.6 (7.2)	None	10,000	Nil	Pitted	Pitted
6.6 (2)	40 g/l 60 Mesh Sand	2,000	0.1 (0.0025)	3.9 (0.10)	2.0 (0.05)
6.6 (2)	40 g/l 10 Mesh Emery	2,000	0.5 (0.0125)	Severe Erosion	Severe Erosion
11.5 (3.5)	1% 80 Mesh Emery	17.5	0.15 (0.0037)	1.1 (.028)	—
13.5 (4.1)	4% 80 Mesh Emery	17.5	3.3 (0.083)	2.6 (.065)	—
23.6 (7.2)	40% 80 Mesh Emery	1	59.1 (1.5)	78.7 (2.0)	—

* High iron, high manganese 70–30 cupro-nickel.

Table 8— Erosion of Unalloyed Titanium in Seawater Locations⁽¹⁵⁾

Location	Flow Rate ft/sec (m/sec)	Duration Months	Corrosion Rate – mpy (mm/y)		
			TIMETAL® 50A	70 Cu-30 Ni*	Aluminum
Brixham Sea	32.2 (9.8)	12	<0.098 (<0.0025)	11.8 (0.3)	39.4 (1.0**)
Kure Beach	3.3 (1)	54	3×10^{-5} (0.75×10^{-6})	—	—
	27.9 (8.5)	2	4.9×10^{-3} (0.000125)	1.9 (0.048)	—
	29.5 (9)	2	1.1×10^{-2} (0.000275)	81.1 (2.06)	—
	23.6 (7.2 [Plus Air])	1	0.020 (0.0005)	4.7 (0.12)	—
Wrightsville Beach	2.0-4.3 (0.6-1.3)	6	0.004 (0.0001)	0.9 (0.022)	—
	29.5 (9)	2	0.007 (0.000175)	—	—
Mediterranean Sea	23.6 (7.2 [Plus Air])	0.5	0.5 mg/day	8.9 mg/day	19.3 mg/day
Dead Sea	23.6 (7.2 [Plus Air])	0.5	0.2 mg/day	9 mg/day	6.7 mg/day

* High iron 70–30 cupro-nickel. ** Sample perforated.

(Table 7). Titanium is considered one of the best cavitation-resistant materials available for seawater service⁽¹⁵⁾ (Table 8).

Stress Corrosion Cracking

TIMETAL® 35A and **50A** are essentially immune to stress-corrosion cracking (SCC) in seawater. This has been confirmed many times as reviewed by Blackburn et al (1973).⁽¹⁶⁾ Other unalloyed titanium grades with oxygen levels greater than 0.2% may be susceptible to SCC under some conditions. Some titanium alloys may be susceptible to SCC in seawater if highly-stressed, preexisting cracks are present. **TIMETAL® 6-4 ELI** (low oxygen content) is considered one of the best of the high strength titanium-base alloys for seawater service.⁽¹⁷⁾

Corrosion Fatigue

Titanium, unlike many other materials, does not suffer a significant loss of fatigue properties in seawater.^(11, 18, 19) This is illustrated by the data in Table 9.

Biofouling

Titanium does not display any toxicity toward marine organisms. Biofouling can occur on surfaces immersed in seawater.

Cotton et al (1957) reported extensive biofouling on titanium after 800 hours immersion in shallow seawater.⁽¹¹⁾ The integrity of the corrosion resistant oxide film, however, is fully maintained under marine deposits and no pitting or crevice corrosion has been observed.

It has been pointed out that marine fouling of titanium heat exchanger surfaces can be minimized by maintaining water velocities in excess of 2 m/sec.⁽²⁰⁾ Chlorination is recommended for protection of titanium heat exchanger surfaces from biofouling where seawater velocities less than 2 m/sec are anticipated.

Crevice Corrosion

Localized pitting or crevice corrosion is a possibility on unalloyed titanium in seawater at temperatures above 180°F (82°C). **TIMETAL® Code-12** and **50A Pd** offer resistance to crevice corrosion in seawater at temperatures as high as 500°F (260°C) and are discussed more thoroughly in the section on chlorides.

Galvanic Corrosion

Titanium is not subject to galvanic corrosion in seawater, however, it may accelerate the corrosion of the other member of the galvanic couple (see Galvanic Corrosion).

Table 9 – Effect of Seawater on Fatigue Properties of Titanium^(11, 19)

Alloy	Stress to Cause Failure in 10 ⁷ Cycles,* Ksi (MPa)	
	Air	Seawater
Unalloyed	52 (359)	54 (372)
TIMETAL® 6-4	70 (480)	60 (410)

*Rotating beam fatigue tests on smooth, round bar specimens.

Acids

Oxidizing Acids

Titanium is highly resistant to oxidizing acids over a wide range of concentrations and temperatures. Common acids in this category include nitric, chromic, perchloric, and hypochlorous (wet Cl_2) acids. These oxidizing compounds assure oxide film stability. Low, but finite, corrosion rates from continued surface oxidation may be observed under high temperature, highly oxidizing conditions.

Titanium has been extensively utilized for handling and producing nitric acid^(4, 21) in applications where stainless steels have exhibited significant uniform or intergranular attack (Table 10). Titanium offers excellent resistance over the full concentration range at sub-boiling temperatures. At higher temperatures, however, titanium's corrosion resistance is highly dependent on nitric acid purity. In hot, very pure solutions or vapor condensates of nitric acid, significant general corrosion (and trickling acid condensate attack) may occur in the 20 to 70 wt. % range as seen in Figure 5. Under marginal high temperature conditions, higher purity unalloyed grades of titanium (i.e., **TIMETAL® 35A**) are preferred for curtailing accelerated corrosion of weldments.

On the other hand, various metallic species such as Si, Cr, Fe, Ti or various precious metal ions (i.e., Pt, Ru) in very minute amounts tend to inhibit high temperature corrosion of titanium in nitric acid solutions (Table 11). Titanium often exhibits superior performance to stainless steel alloys in high temperature metal-contaminated nitric acid media, such as those associated with the Purex Process for U_3O_8 recovery. Titanium's own corrosion product Ti^{4+} , is a very potent inhibitor as shown in Table 12. This is particularly useful in recirculating nitric acid process streams, such as stripper reboiler loops (Table 10), where effective inhibition results from achievement of steady-state levels of dissolved Ti^{4+} .

Table 10 — Corrosion of Titanium and Stainless Steel Heating Surfaces Exposed to Boiling 90% Nitric Acid (215F)⁽²³⁾

Metal Temperature °F (°C)	Corrosion Rate — mpy (mm/y)	
	TIMETAL® 50A	Type 304L Stainless Steel
240 (116)	1.1-6.6 (0.03-0.17)	150-518 (3.8-13.2)
275 (135)	1.6-6.1 (0.04-0.15)	676-2900 (17.2-73.7)
310 (154)	1.0-2.3 (0.03-0.06)	722-2900 (18.3-73.7)

Table 11 — Effect of Chromium on Corrosion of Stainless Steel and Titanium in Boiling HNO_3 (68% *)⁽²³⁾

Percent Chromium	Corrosion Rate — mpy (mm/y)	
	Type 304L (Annealed)	TIMETAL® 50A
0.0	12-18 (0.30-0.46)	3.5-3.8 (0.09-0.10)
0.0005	12-20 (0.30-0.51)	—
0.005	60-90 (1.5-2.3)	0.9-1.6 (0.022-0.041)
0.05	980-1600 (24.9-40.6)	—
0.01	—	0.1-1.4 (0.003-0.036)

* Exposed for three 48-hr. periods, acid changed each period.

Table 12 — Effect of Dissolved Titanium on the Corrosion Rate of Unalloyed Titanium in Boiling Nitric Acid Solutions⁽²²⁾

Titanium Ion Added (mg/l)	Corrosion Rate — mpy (mm/y)	
	40% HNO_3	68% HNO_3
0	29.5 (0.75)	31.8 (0.81)
10	—	0.8 (0.02)
20	8.6 (0.22)	2.4 (0.06)
40	1.9 (0.05)	0.4 (0.01)
80	0.8 (0.02)	0.4 (0.01)

Duration of test: 24 hours

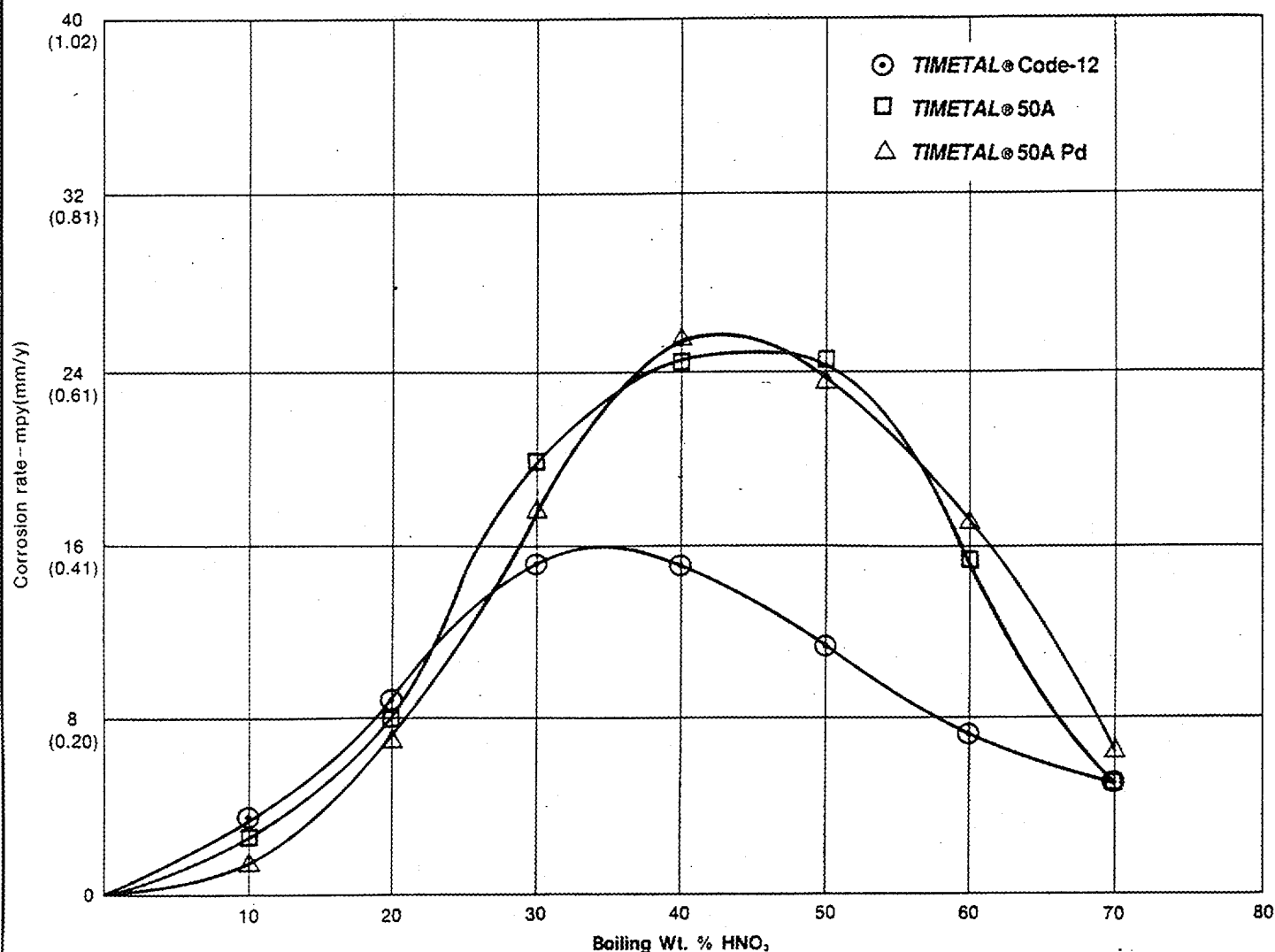


Figure 5 – Resistance of Titanium to Pure Nitric Acid

The data in Table 13 shows that titanium also offers good resistance to nitric acid vapors.

CAUTION: Titanium is not recommended for use in red fuming nitric acid because of the danger of pyrophoric reactions.

Table 13 – Resistance of Titanium to Corrosion by HNO₃ Vapors

Alloy	Corrosion Rate – mpy (mm/y)*
TIMETAL® 50A	2.0 (0.051)
TIMETAL® Code-12	0.8 (0.020)
TIMETAL® 50A Pd	0.08 (0.002)

*Samples suspended in vapors above boiling 70% HNO₃ Azeotrope. 144 hour exposure.

Red Fuming Nitric Acid

Although titanium in general has excellent resistance to nitric acid over a wide range of concentrations and temperatures, it should not be used with red fuming nitric acid. A pyrophoric reaction product can be produced resulting in serious accidents. An investigation of these accidents has shown that the pyrophoric reaction is always preceded by a rapid corrosive attack on the titanium.^(24, 25) This attack is intergranular and results in a surface residue of finely divided particles of metallic titanium. These are highly pyrophoric and are capable of detonating in the presence of a strong oxidizing agent such as fuming nitric acid.

It has been established that the water content of the solution must be less than 1.34% and the NO_2 content greater than 6% for the pyrophoric reaction to develop. This relationship is shown in Figure 6.⁽²⁴⁾

Chromic Acid

The data on chromic acid is not as extensive as that on nitric acid. However, the corrosion resistance of titanium to chromic acid appears to be very similar to that observed in nitric acid. This is shown by the data in Table 14 and by service experience.

Reducing Acids

Titanium offers moderate resistance to reducing acids such as hydrochloric, sulfuric, and phosphoric. Corrosion rates increase with increasing acid concentration and temperature. The **TIMETAL® 50A Pd** alloy offers best resistance to these environments, followed by **TIMETAL® Code-12**, unalloyed titanium, and **TIMETAL® 6-4**.

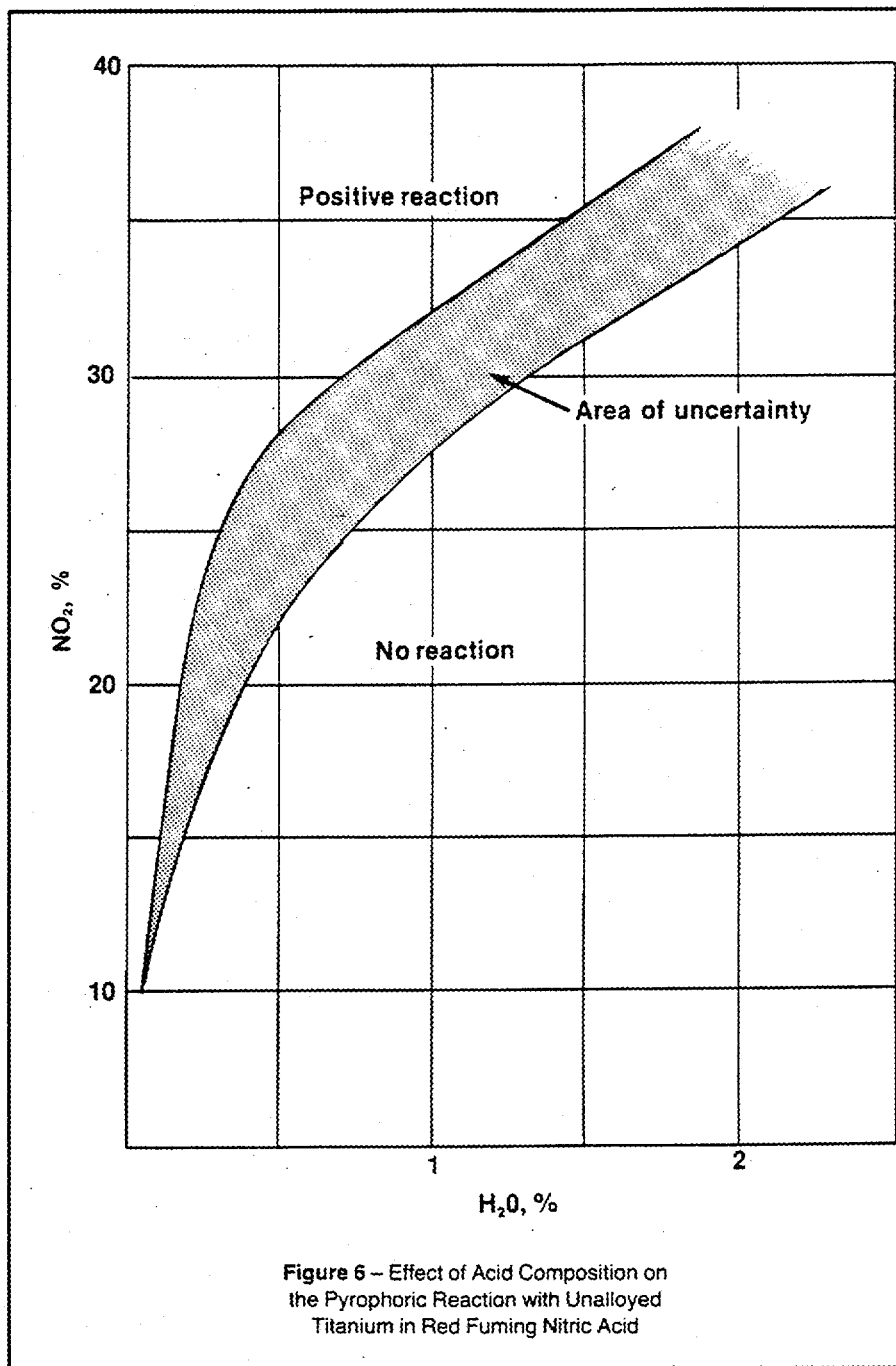


Table 14 – Corrosion of Unalloyed Titanium in Chromic Acid

Acid Concentration %	Temp. °F (°C)	Corrosion Rate mpy (mm/y)	Reference
20	70 (21°)	4.0 Max (0.102 Max)	(26)
10	Boiling	Nil	(27)
10	Boiling	<5.0 (<0.127)	(28)
20	Room	Nil	(29)

Hydrochloric Acid

Iso-corrosion data illustrate that **TIMETAL® 50A** offers useful corrosion resistance to about 7% hydrochloric acid at room temperature; **TIMETAL® Code-12** to about 9% HCl; and **TIMETAL® 50A Pd** to about 27% (See Figure 7). This resistance is significantly lowered at near boiling temperatures.

Typical corrosion rate data for **TIMETAL® 50A**, 6-4, Code-12 and 50A Pd in pure HCl solutions are given in Table 15.

Small amounts of certain multi-valent metal ions in solution, such as ferric ion, can effectively inhibit the corrosion of titanium in hydrochloric acid (Figures 8-10). When sufficient ferric ion is present, **TIMETAL® 50A**, Code-12 and 50A Pd show similar corrosion resistance. Other metal ions, such as Cu^{+2} , Ni^{+2} , Mo^{+6} , and Ti^{+4} , also passivate titanium against attack by hydrochloric acid. Oxidizing agents such as nitric acid, chlorine, sodium hypochlorite, or chromate ions, also have been shown to be effective inhibitors. These have allowed titanium to be successfully utilized in many hydrochloric acid applications.

Severe corrosion damage on titanium equipment has resulted from cleaning procedures utilizing pure hydrochloric acid or acid inhibited with amines. If hydrochloric or sulfuric acid is used to clean titanium surfaces, it is recommended that sufficient ferric chloride be added to effectively inhibit corrosion of the titanium.

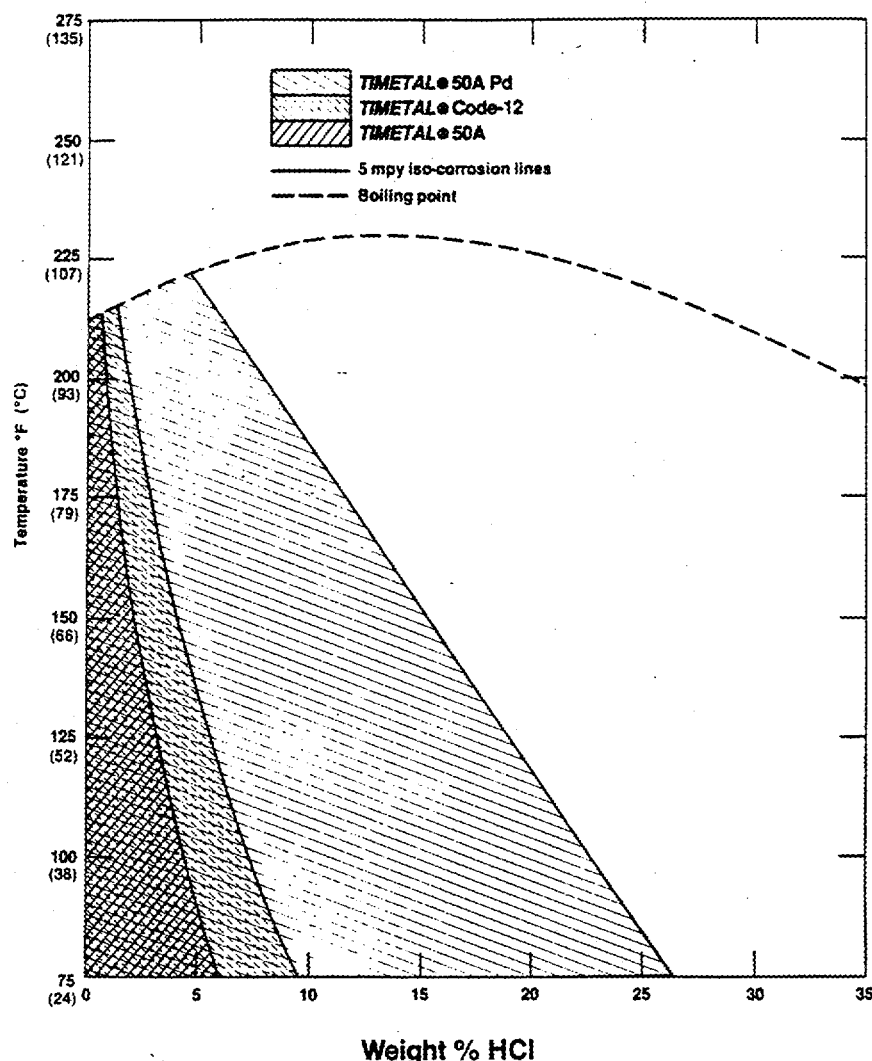


Figure 7 – Corrosion of Titanium Alloys in Naturally Aerated HCl Solutions.

Table 15 – Corrosion of Titanium in Dilute Pure Hydrochloric Acid

Wt. % HCl	FeCl_3 added	Temperature	TIMETAL® 50A	Corrosion Rate – mpy (mm/y)		
				TIMETAL® 6-4	TIMETAL® Code-12	TIMETAL® 50A Pd
1	—	Room	Nil	—	0.2 (0.005)	0.1 (0.003)
2	—	Room	Nil	—	0.1 (0.003)	0.2 (0.006)
3	—	Room	0.5 (0.013)	—	0.5 (0.013)	0.4 (0.010)
5	—	Room	0.2 (0.005)	—	0.5 (0.013)	0.6 (0.015)
8	—	Room	0.2 (0.005)	—	0.2 (0.005)	0.1 (0.025)
1	—	Boiling	85 (2.16)	—	1.4 (0.036)	0.8 (0.020)
2	—	Boiling	280 (7.11)	260 (6.60)	10.0 (0.254)	1.8 (0.046)
3	—	Boiling	550 (14.0)	520 (13.2)	400 (10.2)	2.7 (0.069)
5	—	Boiling	840 (21.3)	1030 (26.2)	1500 (38.1)	10.0 (0.254)
8	—	Boiling	>2000 (>50.8)	1900 (48.3)	3000 (76.2)	24.0 (0.610)
3	2g/l	200F (93°C)	0.2 (0.005)	—	1.0 (0.025)	0.1 (0.003)
4	2g/l	200F (93°C)	0.4 (0.010)	—	2.0 (0.050)	0.3 (0.008)

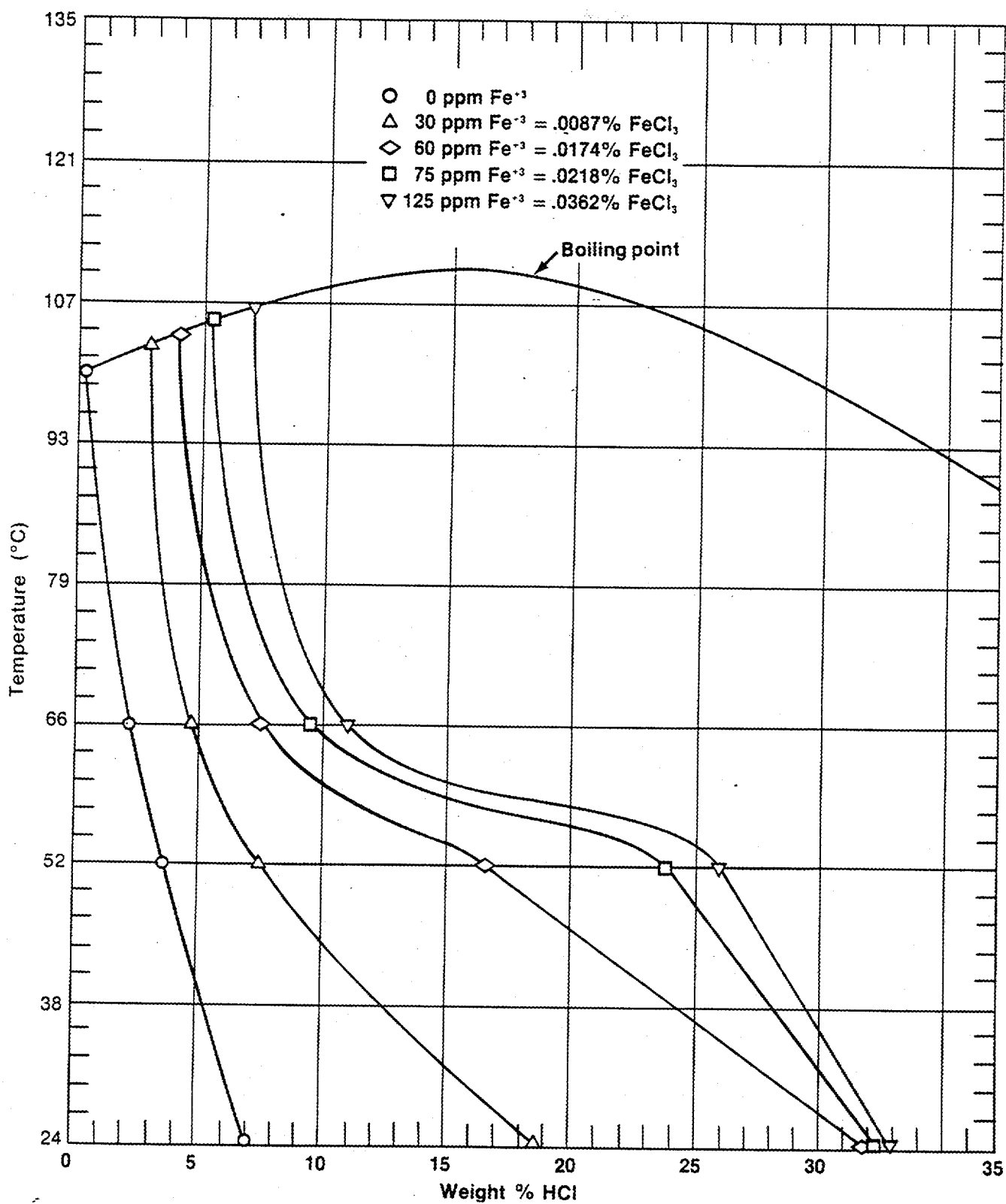


Figure 8—Effect of Ferric Ions on the Corrosion of
TIMETAL® 50A. 5 mpy (0.127 mm/y) Iso-Corrosion Line.

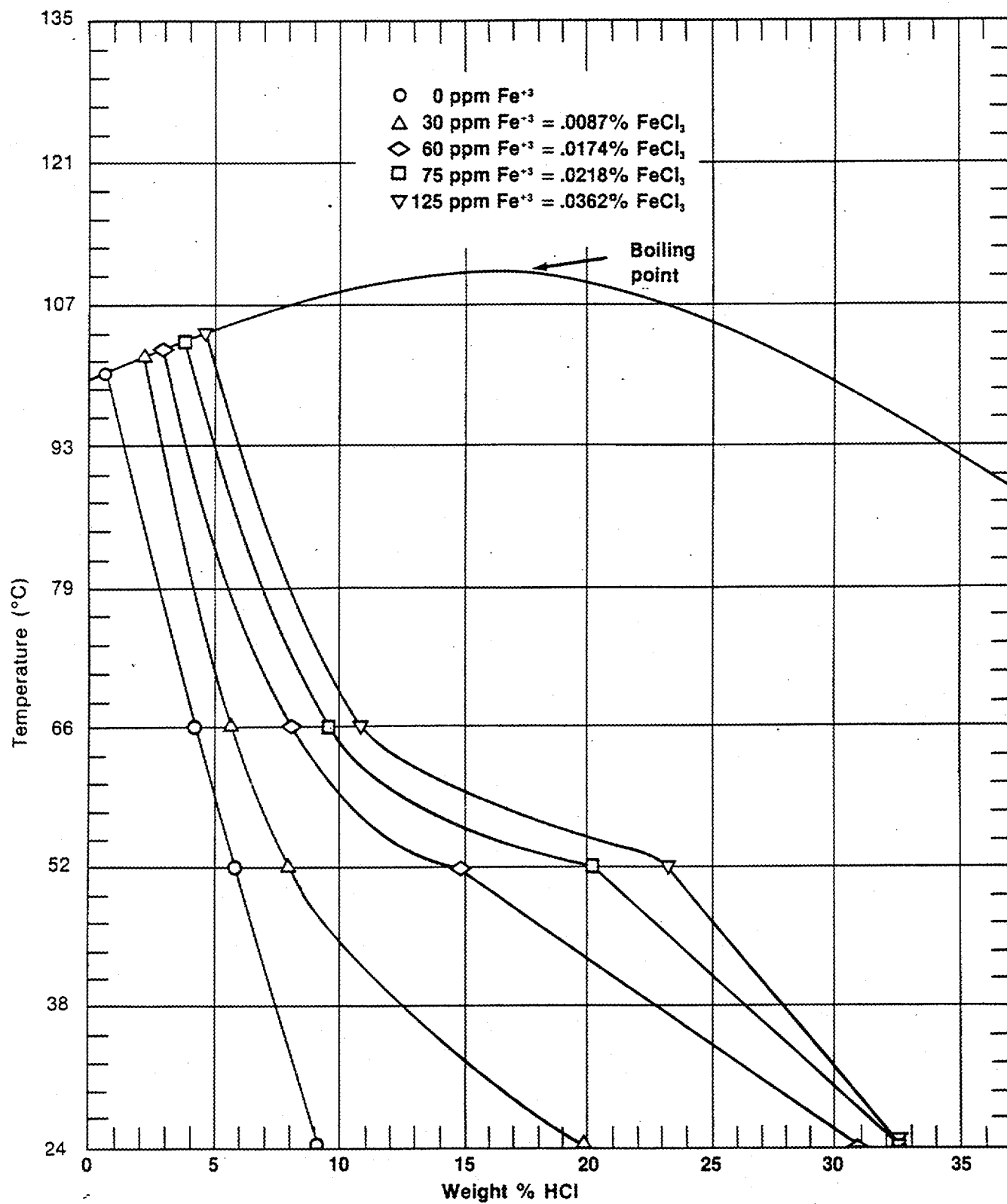


Figure 9—Effect of Ferric Ions on the Corrosion of **TIMETAL**® Code-12, 5 mpy (0.127 mm/y) Iso-Corrosion Line.

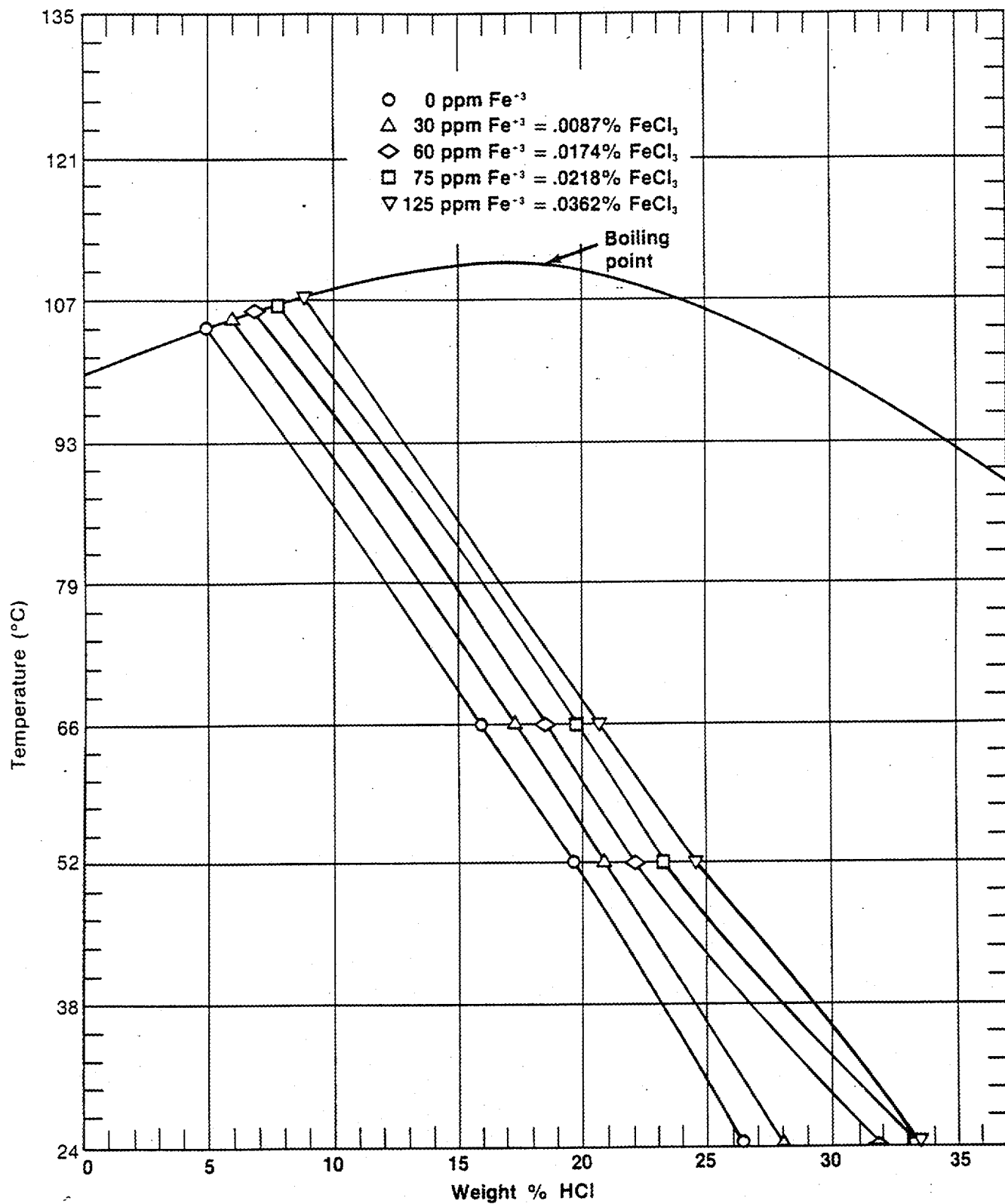


Figure 10—Effect of Ferric Ions on the Corrosion of **TIMETAL® 50A** Pd. 5 mpy (0.127 mm/y) Iso-Corrosion Line.

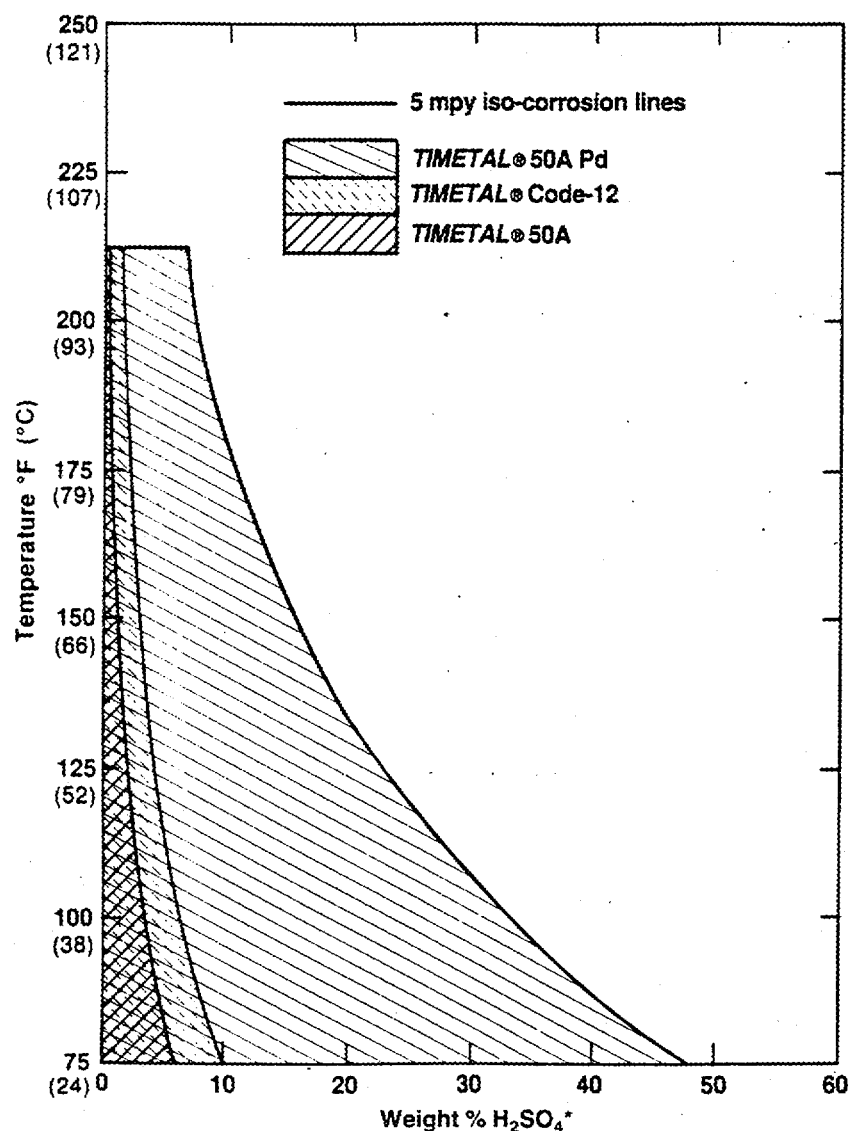


Figure 11 – Iso-Corrosion Chart for Titanium Alloys H₂SO₄ Solutions.
*Naturally Aerated

Table 16 – Effect of Inhibitors on the Corrosion of Unalloyed Titanium in 20 Percent Sulfuric Acid

% H ₂ SO ₄	Addition	Temperature °F (°C)	Corrosion Rate mpy (mm/y)
20	None	210 (99)	>2400 (>61.8)
20	2.5 Grams Per Liter Copper Sulfate	210 (99)	<2 (<0.051)
20	16 Grams Per Liter Ferric Ion	Boiling	5 (0.127)

Sulfuric Acid

Titanium is resistant to corrosive attack by dilute solutions of pure sulfuric acid at low temperatures. At 32°F (0°C), unalloyed titanium is resistant to concentrations of about 20 percent sulfuric acid. This decreases to about 5 percent acid at room temperature (Figure 11). **TIMETAL® 50A Pd** is resistant to about 45 percent acid at room temperature. In boiling sulfuric acid, unalloyed titanium will show high corrosion rates in solutions with as little as 0.5 percent sulfuric acid. **TIMETAL® Code-12** has useful resistance up to about 1 percent boiling acid. **TIMETAL® 50A Pd** is useful in boiling sulfuric acid to about 7 percent concentration. The **TIMETAL® 6-4** alloy has somewhat less resistance than unalloyed titanium.

The presence of certain multi-valent metal ions or oxidizing agents in sulfuric acid inhibit the corrosion of titanium in a manner similar to hydrochloric acid. For instance, cupric and ferric ions inhibit the corrosion of unalloyed titanium in 20 percent sulfuric acid (Table 16). Oxidizing agents, such as nitric acid, chromic acid, and chlorine are also effective inhibitors.

Phosphoric Acid

Unalloyed titanium is resistant to naturally aerated pure solutions of phosphoric acid up to 30 percent concentration at room temperature (Figure 12). This resistance extends to about 10 percent pure acid at 140°F (60°C) and 2 percent acid at 212°F (100°C). Boiling solutions significantly accelerate attack.

TIMETAL® 50A Pd offers significantly improved resistance. At room temperature, 140°F (60°C), and boiling, **TIMETAL® 50A Pd** will resist concentrations of about 80, 15 and 6 percent, respectively, of the pure phosphoric acid. **TIMETAL® Code-12** offers somewhat better resistance to phosphoric acid than unalloyed titanium, but not as good as **TIMETAL® 50A Pd**.

The presence of multi-valent metal ions, such as ferric or cupric, or oxidizing species can be used to inhibit titanium corrosion in phosphoric acid.

Hydrofluoric Acid

Titanium is rapidly attacked by hydrofluoric acid of even very dilute concentrations. Therefore, titanium is not recommended for use with hydrofluoric acid solutions or in fluoride containing solutions below pH 7. Certain complexing metal ions (i.e., Al³⁺, Cr⁶⁺) may effectively inhibit corrosion in dilute fluoride solutions.

Sulfurous Acid

Corrosion of unalloyed titanium in sulfurous acid is low: 0.02 mpy (0.0005 mm/y) in 6 percent concentration at room temperature. Samples exposed to sulfurous acid (6 percent sulfur dioxide content) 212°F (100°C) showed a corrosion rate of 0.04 mpy (0.001 mm/y).

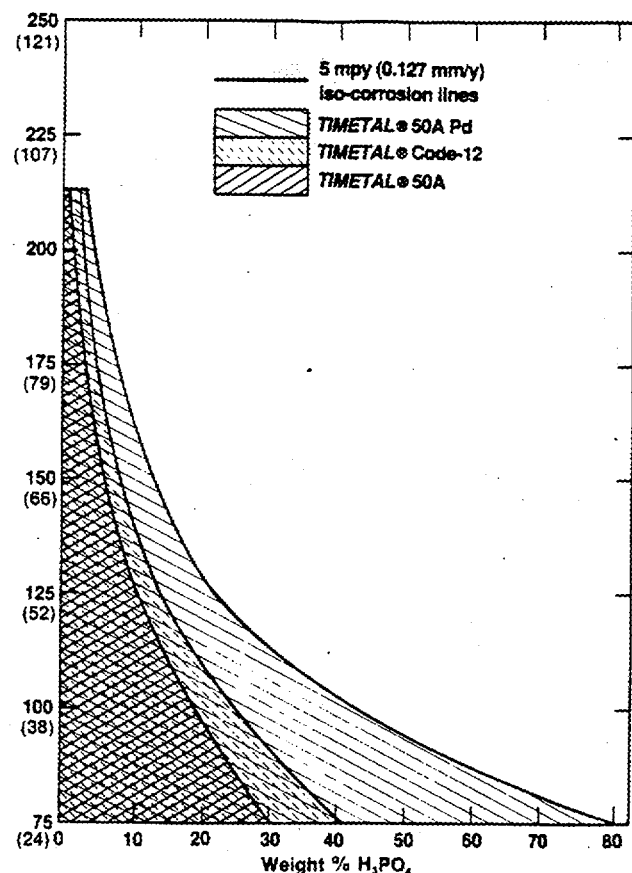


Figure 12 – Corrosion of Titanium Alloys in Naturally Aerated H_3PO_4 Solutions.

Table 17 – Resistance of Titanium to Corrosion by Boiling Aqua Regia*

Alloy	Corrosion Rate – mpy (mm/y)
TIMETAL® 50A	44 (1.12)
TIMETAL® Code-12	24 (0.61)
TIMETAL® 50A Pd	44 (1.12)

* (1 part HNO_3 : 3 parts HCl, 96 hour tests)

Table 18 – Corrosion Rates of Unalloyed Titanium in NaOH and KOH Solutions

Wt%		Temp °F (°C)	Corrosion Rate mpy (mm/y)
5-10	NaOH	70 (21)	0.04 (0.001)
40	NaOH	150 (66)	1.5 (0.038)
40	NaOH	200 (93)	2.5 (0.064)
40	NaOH	250 (121)	5.0 (0.127)
50	NaOH	100 (38)	0.06 (0.002)
50	NaOH	150 (66)	0.7 (0.018)
50	NaOH	250 (121)	1.3 (0.033)
50-73	NaOH	370 (188)	>43 (>1.09)
73	NaOH	230 (110)	2.0 (0.051)
73	NaOH	240 (116)	5.0 (0.127)
73	NaOH	265 (129)	7.0 (0.178)
75	NaOH	250 (121)	1.3 (0.033)
10	KOH	217 (103)	5.1 (0.13)
25	KOH	226 (108)	11.8 (0.30)

Other Inorganic Acids

Titanium offers excellent resistance to corrosion by several other inorganic acids. It is not significantly attacked by boiling 10 percent solutions of boric or hydriodic acids. At room temperature, low corrosion rates are obtained on exposure to 50 percent hydrochloric and 40 percent hydrobromic acid solutions.⁽³⁰⁾

Mixed Acids

The addition of nitric acid to hydrochloric or sulfuric acids significantly reduces corrosion rates. Titanium is essentially immune to corrosion by aqua regia (3 parts HCl: 1 part HNO_3) at room temperature. TIMETAL® 50A, Code-12 and 50A Pd show respectable corrosion rates in boiling aqua regia (Table 17). Corrosion rates in mixed acids will generally rise with increases in the reducing acid component concentration or temperature.

Alkaline Media

Titanium is generally very resistant to corrosion in alkaline media including solutions of sodium hydroxide, potassium hydroxide, calcium hydroxide and ammonium hydroxide. At concentrations of up to approximately 70% for example, titanium exhibits corrosion rates of less than or equal to 5 mpy [(0.127 mm/y) Table 18.] Near nil corrosion rates are exhibited in boiling calcium hydroxide, magnesium hydroxide, and ammonium hydroxide solutions up to saturation.

Despite low corrosion rates in alkaline solutions, hydrogen pickup and possible embrittlement of titanium can occur at temperatures above 170°F (77°C) when solution pH is greater than or equal to 12. Successful application can be achieved where this guideline is observed.

Inorganic Salt Solutions

Titanium is highly resistant to corrosion in inorganic salt solutions. Corrosion rates are generally very low at all temperatures to the boiling point. The resistance of titanium to chloride solutions is excellent (Table 3). However, crevice corrosion is a concern as illustrated in Figures 2, 3 and 4. Other acidic salt solutions, particularly those formed from reducing acids, may also cause crevice corrosion of unalloyed titanium at elevated temperatures. For instance, a boiling solution of 10 percent sodium sulfate, pH 2.0, causes crevice corrosion on TIMETAL® 50A (Table 4). The TIMETAL® Code-12 and 50A Pd alloys, on the other hand, are resistant to this environment.

Table 19 – Resistance of Unalloyed Titanium to Organic Compounds⁴⁴

Medium	Concentration %	Temperature F (°C)	Corrosion Rate – mpy (mm/y)
Acetic anhydride	99-99.5	68-Boiling (20-Boiling)	<5 (<0.127)
Adipic acid – 15-20% glutaric + acetic	25	380-392 (193-200)	Nil
Adiponitrile solution	Vapor	700 (371)	0.3 (0.008)
Adipyl-chloride – chlorobenzene	–	–	0.1 (0.003)
Aniline hydrochloride	5-20	95-212 (35-100)	<0.03 (<0.001)
Aniline – 2% aluminum chloride	98	600 (316)	804 (20.4)
Benzene + HCl, NaCl	Vapor & Liquid	176 (80)	0.2 (0.005)
Carbon tetrachloride	99	Boiling	<5 (<0.127)
Chloroform	100	Boiling	0.01 (0.000)
Chloroform – water	–	Boiling	5 (0.127)
Cyclohexane – traces formic acid	–	302 (150)	0.1 (0.003)
Ethylene dichloride	100	Boiling	<5 (<0.127)
Formaldehyde	37	Boiling	<5 (<0.127)
Tetrachloroethylene	100	Boiling	<5 (<0.127)
Tetrachloroethane	100	Boiling	<5 (<0.127)
Trichlorethylene	99	Boiling	<0.1 (<0.003)

Organic Chemicals

Titanium generally shows good corrosion resistance to organic media (Table 19) and is steadily finding increasing application in equipment for handling organic compounds. Kane⁴ points out that titanium is a standard construction material in the Wacker Process for the production of acetaldehyde by oxidation of ethylene in an aqueous solution of metal chlorides. Successful application has also been established in critical areas of terephthalic and adipic acid production.

Generally, the presence of moisture (even trace amounts) and oxygen is very beneficial to the passivity of titanium in organic media. In certain anhydrous organic media, titanium passivity can be difficult to maintain. For example, methyl alcohol can cause stress corrosion cracking in unalloyed titanium (see Stress Corrosion Cracking) when the water content is below 1.5%.^{31, 32} At high temperatures in anhydrous environments where dissociation of the organic compound can occur, hydrogen embrittlement of the titanium may be possible. Since many organic processes contain either trace amounts of water and/or oxygen, titanium has found successful application in organic process streams.

Table 20 – Resistance of Unalloyed Titanium to Organic Acids³³

Acid	Concentration %	Temperature F (°C)	Corrosion Rate mpy (mm/y)
Acetic	5	212 (100)	Nil
Acetic	25	212 (100)	Nil
Acetic	50	212 (100)	Nil
Acetic	75	212 (100)	Nil
Acetic	99.5	212 (100)	Nil
Citric	50	212 (100)	<.01 (<0.0003)
Citric (aerated)	50	212 (100)	<5 (<0.127)
Citric (nonaerated)	50	Boil	14 (0.356)
Formic (aerated)	10	212 (100)	<5 (<0.127)
Formic (aerated)	25	212 (100)	<5 (<0.127)
Formic (aerated)	50	212 (100)	<5 (<0.127)
Formic (aerated)	90	212 (100)	<5 (<0.127)
Formic (nonaerated)	10	Boil	>50 (>1.27)
Formic (nonaerated)	25	Boil	>50 (>1.27)
Formic (nonaerated)	50	Boil	>50 (>1.27)
Formic (nonaerated)	90	Boil	>50 (>1.27)
Lactic	10	140 (60)	0.12 (0.003)
Lactic	10	212 (100)	1.88 (0.048)
Lactic	85	212 (100)	0.33 (0.008)
Lactic (nonaerated)	10	Boil	0.55 (0.014)
Lactic (nonaerated)	25	Boil	1.09 (0.028)
Lactic (nonaerated)	85	Boil	0.40 (0.010)
Oxalic	1	95 (35)	5.96 (0.151)
Oxalic	1	140 (60)	177 (4.50)
Oxalic	25	212 (100)	1945 (49.4)
Stearic	100	360 (182)	<5 (<0.127)
Tartaric	50	212 (100)	0.2 (0.005)
Tannic	25	212 (100)	Nil

Table 21 – Resistance of Titanium to Boiling Nonaerated Organic Acids

Acid Solution	Corrosion Rate – mpy (mm/y)		
	TIMETAL® 50A	TIMETAL® Code-12	TIMETAL® 50A Pd
50% Citric	14 (0.356)	0.5 (0.01)	0.6 (0.015)
10% Sulfamic	538 (13.7)	455 (11.6)	14.6 (0.371)
45% Formic	433 (11.0)	Nil	Nil
88-90% Formic	83-141 (2.1-3.6)	0-22 (0-0.56)	0-2.2 (0-0.056)
90% Formic (Anodized Specimens)	90 (2.29)	2.2 (0.056)	Nil
10% Oxalic	3,700 (94.0)	4,100 (104)	1,270 (32.3)

Organic Acids

Titanium is generally quite resistant to organic acids.¹³³ Its behavior is dependent on whether the environment is reducing or oxidizing. Only a few organic acids are known to attack titanium. Among these are hot non-aerated formic acid, hot oxalic acid, concentrated trichloroacetic acid and solutions of sulfamic acid. Aeration improves the resistance of titanium in most of these nonoxidizing acid solutions. In the case of formic acid, it reduces the corrosion rates to very low values (Table 20).

Unalloyed titanium corrodes at a very low rate in boiling 0.3 percent sulfamic acid and at a rate of over 100 mpy (2.54 mm/y) in 0.7 percent boiling sulfamic acid. Addition of ferric chloride (0.375 g/l) to the 0.7 percent solution reduces the corrosion rate to 1.2 mpy (0.031 mm/y).

Boiling solutions containing more than 3.5 g/l of sulfamic acid can rapidly attack unalloyed titanium. For this reason, extreme care should be exercised when titanium heat exchangers are descaled with sulfamic acid. The pH of the acid should not be allowed to go below 1.0 to avoid corrosion of titanium. Consideration should also be given to inhibiting the acid with ferric chloride.

Titanium is resistant to acetic acid¹³⁴ over a wide range of concentrations and temperatures well beyond the boiling point. It is being used in terephthalic acid and adipic acid up to 400°F (204°C), and at 67% concentration. Good resistance is observed in citric, tartaric, stearic, lactic and tannic acids (see Table 20).

TIMETAL® Code-12 and **50A Pd** may offer considerably improved corrosion resistance to organic acids which attack unalloyed titanium (Table 21). Similarly, the presence of multi-valent metal ions in solution may result in substantially reduced corrosion rates.

Oxygen

Titanium has excellent resistance to gaseous oxygen and air at temperatures up to about 700°F (371°C). At 700°F it acquires a light straw color. Further heating to 800°F (426°C) produces a blue color, as the oxide film thickens. Long exposures of titanium to temperatures above 800°F (426°C) in air may result in a heavy oxide layer because of increased diffusion of oxygen through the titanium lattice. Above 1,200°F (649°C), titanium lacks oxidation resistance and will become brittle. Scale forms rapidly at 1,700°F (927°C).

Titanium resists atmospheric corrosion. Twenty year ambient temperature tests produced a maximum corrosion rate of 0.0010 mpy (2.54×10^{-5} mm/y) in a marine atmosphere and a similar rate in industrial and rural atmospheres.³⁴¹

Caution should be exercised in using titanium in high oxygen atmospheres. Under some conditions, it may ignite and burn. J. D. Jackson and Associates reported that ignition cannot be induced even at very high pressure when the oxygen content of the environment was less than 35%.³⁵¹ However, once the reaction has started, it will propagate in atmospheres with much lower oxygen levels than are needed to start it. Steam as a diluent allowed the reaction to proceed at even lower O_2 levels. The temperature, oxygen pressure, and concentration limits under which ignition and propagation occur are shown in figures 13 and 14. When a fresh titanium surface is exposed to an oxygen atmosphere, it oxidizes rapidly and exothermically. Rate of oxidation depends on O_2 pressure and concentration. When the rate is high enough so that heat is given off faster than it can be conducted away, the surface may begin to melt. The reaction becomes self-sustaining because, above the melting point, the oxides diffuse rapidly into the titanium interior, allowing highly reactive fresh molten titanium to react at the surface.

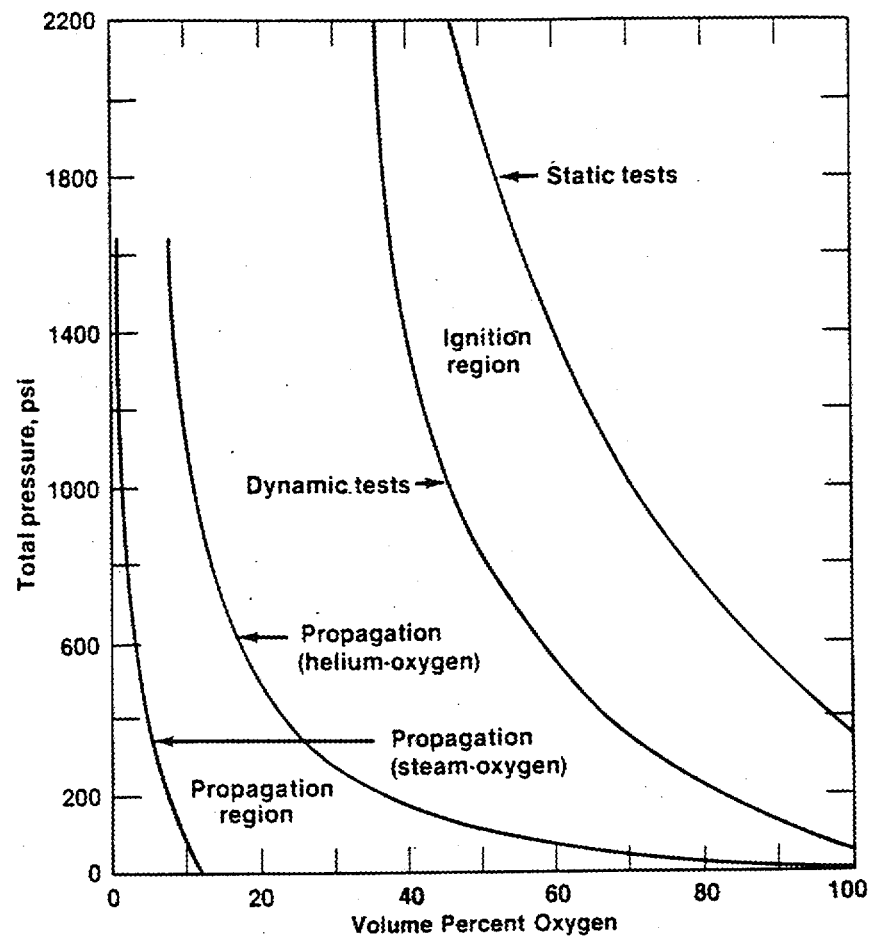


Figure 13 – Ignition and Propagation Limits of Unalloyed Titanium in Helium-Oxygen and Steam-Oxygen Mixtures³⁶¹

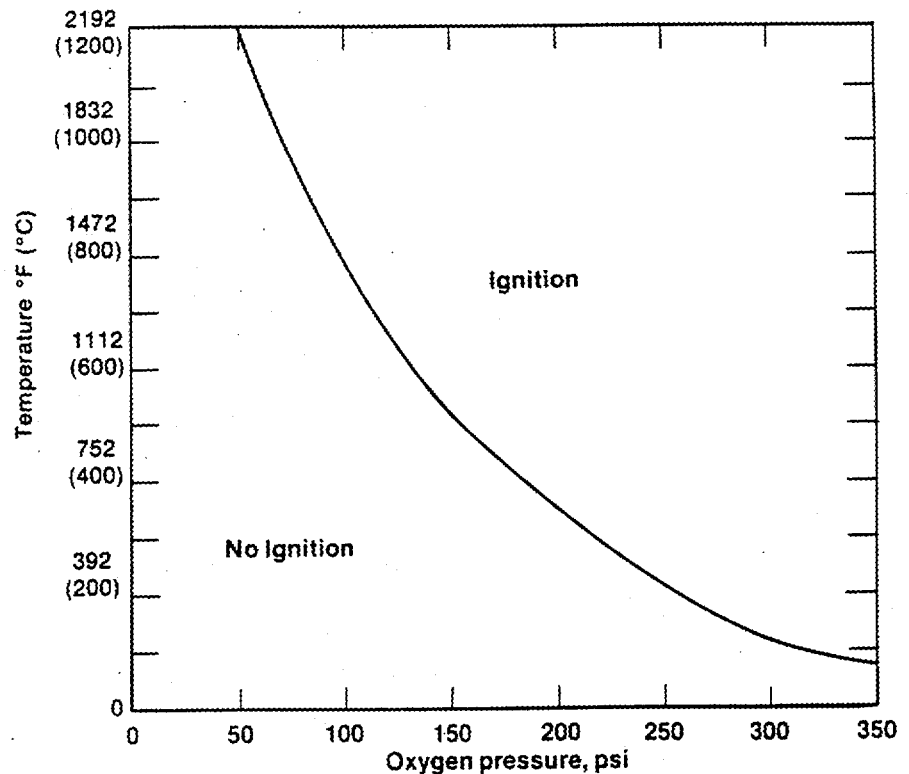


Figure 14 – Effect of Temperature on Spontaneous Ignition of Ruptured Unalloyed Titanium in Oxygen³⁶¹

Hydrogen

The surface oxide film on titanium acts as an effective barrier to penetration by hydrogen. Disruption of the oxide film allows easy penetration by hydrogen. When the solubility limit of hydrogen in titanium (about 100-150 ppm for **TIMETAL® 50A**) is exceeded, hydrides begin to precipitate. Absorption of several hundred ppm of hydrogen results in embrittlement and the possibility of cracking under conditions of stress.

Titanium can absorb hydrogen from environments containing hydrogen gas. At temperatures below 176°F (80°C) hydrogen pickup occurs so slowly that it has no practical significance, except in cases where severe tensile stresses are present.⁽³⁷⁾ In the presence of pure hydrogen gas under anhydrous conditions, severe hydriding can be expected at elevated temperatures and pressures. This is shown by the data in Table 22. These data also demonstrate that surface condition is important to hydrogen penetration.

Titanium is not recommended for use in pure hydrogen because of the possibility of hydriding if the oxide film is broken. Laboratory tests (Table 23) have shown that the presence of as little as 2% moisture in hydrogen gas effectively passivates titanium so that hydrogen absorption does not occur. This probably accounts for the fact that titanium is being used successfully in many process streams containing hydrogen with very few instances of hydriding being reported.

A more serious situation exists when cathodically impressed or galvanically induced currents generate nascent hydrogen directly on the surface of titanium. The presence of moisture does not inhibit hydrogen absorption of this type.

Laboratory experiments have shown that three conditions usually exist simultaneously for hydriding to occur:⁽³⁸⁾

1. The pH of the solution is less than 3 or greater than 12; the metal surface must be damaged by abrasion; or impressed potentials are more negative than -0.70V.⁽³⁹⁾
2. The temperature is above 176°F (80°C) or only surface hydride films will form which, experience indicates, do not seriously affect the properties of the metal. Failures due to hydriding are rarely encountered below this temperature. (There is some evidence that severe tensile stresses may promote hydriding at low temperatures.)⁽³⁹⁾
3. There must be some mechanism for generating hydrogen. This may be a galvanic couple, cathodic protection by impressed current, corrosion of titanium, or dynamic abrasion of the surface with sufficient intensity to depress the metal

Table 22 – Effect of Various Surface Treatments on Absorption of Dry and Oxygen-Free Hydrogen by Unalloyed Titanium*

Temperature F (°C)	Hydrogen Pressure psi	Freshly Pickled	Hydrogen Pickup, ppm	
			Iron Contaminated	Anodized
300 (149)	Atmospheric	0	0	0
300 (149)	400	58	174	0
300 (149)	800	28	117	0
600 (316)	Atmospheric	0	0	0
600 (316)	400	2,586	5,951	516
600 (316)	800	4,480	13,500	10,000

*96 hour exposures. Oxygen was removed by passing hydrogen over an incandescent platinum filament and then through silica gel to remove moisture

potential below that required for spontaneous evolution of hydrogen.

Most of the hydriding failures of titanium that have occurred in service can be explained on this basis.⁽³⁸⁾

In seawater, hydrogen can be produced on titanium as the cathode by galvanic coupling to a dissimilar metal such as zinc or aluminum which are very active (low) in the galvanic series. Coupling to carbon steel or other metals higher in the galvanic series generally does not generate hydrogen in neutral solutions, even though corrosion is progressing on the dissimilar metal. The presence of hydrogen sulfide, which dissociates readily and lowers pH, apparently allows generation of hydrogen on titanium if it is coupled to actively corroding carbon steel or stainless steel.

Within the range pH 3 to 12, the oxide film on titanium is stable and presents a barrier to penetration by hydrogen. Efforts at cathodically charging hydrogen into titanium in this pH range have been unsuccessful in short-term tests.⁽³⁸⁾ If pH is below 3 or above 12, the oxide film is believed to be unstable and less protective. Breakdown of the oxide film facilitates access of available hydrogen to the underlying titanium metal. Mechanical disruption of the film (i.e. iron is smeared into the surface) permits entry of hydrogen at any pH level. Impressed currents involving cathodic potentials more negative than -0.7V in near neutral brines can result in hydrogen pickup in long-term exposures.⁽³⁹⁾ Furthermore, very high cathodic current densities (more negative than -1.0V SCE) may accelerate hydrogen absorption and eventual embrittlement of titanium in seawater even at ambient temperatures.

Hydriding can be avoided if proper consideration is given to equipment design and service conditions in order to eliminate detrimental galvanic couples or other conditions that will promote hydriding.

Table 23 – Effect of Moisture on Absorption of Hydrogen by Unalloyed Titanium at 600°F (316°C) and 800 psi Pressure*

%H ₂ O	Hydrogen Pickup – ppm
0	4,480
0.5	51,000
1.0	700
2.0	7
3.3	10
5.3	17
10.2	11
22.5	0
37.5	0
56.2	0

*96 hour exposures.

Sulfur Dioxide and Hydrogen Sulfide

Titanium is resistant to corrosion by gaseous sulfur dioxide and water saturated with sulfur dioxide (Table 24). Sulfurous acid solutions also have little effect on titanium. Titanium has demonstrated superior performance in wet SO₂ scrubber environments of power plant FGD systems.

Titanium is not corroded by moist or dry hydrogen sulfide gas. It is also highly resistant to aqueous solutions containing hydrogen sulfide. The only known detrimental effect is the hydriding problem discussed in the previous section. In galvanic couples with certain metals such as iron, the presence of H₂S will promote hydriding. Hydriding, however, does not occur in aqueous solutions containing H₂S if unfavorable galvanic couples are avoided. For example, titanium is fully resistant to corrosion and stress cracking in the NACE* test solution which consists of oxygen-free water containing about 3,000 ppm dissolved H₂S, 5 percent NaCl, and 0.5 percent acetic acid (pH 3.5). Tensile specimens of **TIMETAL® 50A**, **75A**, **50A Pd** and **Code-12** stressed to 98 percent of yield strength in this environment survived a 30-day room temperature exposure.

In addition, C-ring specimens of these same grades of titanium were subjected to a stress corrosion cracking test as specified in ASTM G38-73 Standard Recommended Practice. Two series of tests were run: one with the specimens stressed to 75% of yield, and the other stressed to 100% of yield. The specimens were exposed in an ASTM synthetic seawater solution saturated with H₂S and CO₂ at 400°F (204°C). Solution pH was 3.5 and specimens were exposed for 30 days. There were no failures and no evidence of any corrosion.

Titanium is highly resistant to general corrosion and pitting in the sulfide environment to temperatures as high as 500°F (260°C). Sulfide scales do not form on titanium, thereby maintaining good heat transfer.

*National Association of Corrosion Engineers

Nitrogen and Ammonia

Titanium reacts with pure nitrogen to form surface films having a gold color above 1,000°F (538°C). Above 1,500°F (816°C), diffusion of the nitride into titanium may cause embrittlement.

Jones et al (1977) have shown that titanium is not corroded by liquid anhydrous ammonia at room temperature.⁽⁴⁰⁾ Low corrosion rates are obtained at 104°F (40°C).⁽⁴¹⁾ Titanium also resists gaseous ammonia. However, at temperatures above 302°F (150°C), ammonia will decompose and form hydrogen and nitrogen. Under these circumstances, titanium could absorb hydrogen and become embrittled. The high corrosion rate experienced by titanium in the ammonia-steam environment at 428°F (220°C) in Table 25 is believed to be associated with hydriding.

Table 25 also contains data which illustrate the resistance of titanium to ammonium hydroxide. Excellent resistance is offered by titanium to concentrated solutions (up to 70% NH₄OH) to the boiling point.⁽⁴¹⁾

The formation of ammonium chloride scale could result in crevice corrosion of **TIMETAL® 50A** at boiling temperatures, as shown in Table 25. **TIMETAL® Code-12** and **50A Pd** are totally resistant under these conditions. This crevice corrosion behavior is similar to that shown in Figures 2 and 4 for sodium chloride.

Table 24 – Corrosion of Unalloyed Titanium by Sulfur-Containing Gases⁽³³⁾

Gas	Temperature F (°C)	Corrosion Rate mpy (mm/y)
Sulfur dioxide (dry)	70 (21)	Nil
Sulfur dioxide (water saturated)	70 (21)	<0.1 (<0.003)
Hydrogen sulfide (water saturated)	70 (21)	<5 (<0.127)

Table 25 – Corrosion of Unalloyed Titanium in Ammonia and Ammonium Compounds

Environment	Temperature F (°C)	Duration, Days	Corrosion Rate mpy (mm/y)	References
Liquid Anhydrous Ammonia	75 (24)	30-240	0 to wt. Gain	(40)
Anhydrous Ammonia	104 (40)	—	5.1 (0.13)	(41)
NH ₃ , Steam Water	431 (221)	—	440.0 (11.2)	(41)
28% NH ₄ OH	75 (24)	—	0.10 (0.0025)	(42)
70% NH ₄ OH, Boiling	210 (99)	21	Nil*	(41)
NH ₄ OH, (NH ₄) ₂ CO ₃ , NH ₄ Cl, NaCl	150 (66)	220	0.003 (0.00008)	(43)
NH ₄ OH, (NH ₄) ₂ CO ₃ , NH ₄ Cl, NaCl, (NH ₄) ₂ S	150 (66)	220	0.20 (0.005)	(43)
10% NH ₄ Cl (pH 4.1)	Boiling	21	Nil**	(41)

* No corrosion experienced on **TIMETAL® 50A**, **TIMETAL® Code-12** or **TIMETAL® 50A Pd**.

** No corrosion on **TIMETAL® Code-12** or **TIMETAL® 50A Pd**; crevice corrosion on **TIMETAL® 50A**.

Liquid Metals

Titanium has good resistance to many liquid metals at moderate temperatures. In some cases at higher temperatures it dissolves rapidly. It is used successfully in some applications up to 1,650°F (899°C). Kane cites the use of titanium in molten aluminum for pouring nozzles, skimmer rakes and casting ladles.¹⁴¹ Rapidly flowing molten aluminum, however, can erode titanium; and some metals such as cadmium can cause stress corrosion cracking. Some data for titanium in liquid metals is reported in Table 26.

Anodizing and Oxidation Treatments

Anodizing has been recommended for many years as a method of improving the corrosion resistance of titanium and removing surface impurities such as embedded iron particles.¹⁴⁴ It was reasoned that since titanium's corrosion resistance is due to the oxide film that forms on its surface, any treatment, such as anodizing, which thickens this film will serve to increase the corrosion resistance of titanium.

Careful laboratory tests have shown this may not be true. The films formed on titanium at elevated temperatures in air have been found to have a rutile structure which is quite resistant to acids and can, therefore, improve the corrosion resistance. Anodizing, on the other hand, forms a hydrated structure which is much less resistant to acids.^{145, 146} Tests in boiling HCl solution (Table 27) have shown no significant difference in corrosion resistance between anodized and freshly pickled specimens. Anodizing has been shown to give a marginal improvement in resistance to hydrogen absorption (Table 28) but not nearly as much as thermal oxidation.¹⁴⁵

It is true that anodizing helps to remove surface impurities such as embedded iron particles. However, excessively long anodizing times may be required to completely remove these particles. Examination with a scanning electron microscope has proven that surface iron contamination still persists, although diminished, even after 20 minutes anodizing. A more effective method is to pickle in 12% HNO₃/1% HF at ambient temperature for 5 minutes followed by a water rinse. Specimens known to have embedded iron particles were found to be completely free of any surface iron contamination by the scanning electron microscope following this procedure.

Table 26 – Corrosion of Unalloyed Titanium in Liquid Metal¹⁴¹

Liquid Metal	Temperature °F (°C)	Resistance
Magnesium	1380 (749)	Good
Mercury*	300 (149)	Good
Mercury*	600 (316)	Poor
NaK	1000 (538)	Good
Tin	930 (499)	Good
Gallium	750 (399)	Good
Gallium	840 (449)	Poor
Cadmium*	930 (499)	Poor
Lithium	140 (60)	Poor
Lead	1500 (816)	Poor

*May cause stress corrosion. Silver and gold have also been reported to cause stress corrosion.

Table 27 – Corrosion Rate vs. Weight Percent HCl for Pickled, Anodized and Thermally Oxidized *TIMETAL*® 50A

Boiling wt. % HCl	Corrosion Rate – mpy (mm/y)		
	Pickled	Anodized (+ 25 volts)	Thermally Oxidized (677°C, 1 Min.)
0.05	0.08 (0.002)	0.09 (0.002)	0.11 (0.003)
0.10	3.0 (0.076)	3.5 (0.089)	Nil
0.20	7.6 (0.193)	8.3 (0.211)	0.07 (0.002)
0.50	30.0 (0.762)	30.0 (0.762)	0.07 (0.002)
0.70	47.0 (1.19)	48.3 (1.23)	0.07 (0.002)
0.80	57.9 (1.47)	56.0 (1.42)	0.11 (0.003)
0.90	—	—	73.0 (1.85)
1.00	75.0 (1.91)	80.0 (2.03)	85.8 (2.18)

Table 28 – Effect of Surface Condition of *TIMETAL*® 50A on Hydrogen Uptake from Cathodic Charging

Surface Condition	Average Hydrogen Pickup (ppm)
Pickled	164
Anodized	140
Thermally Oxidized (677°C) (1 min.)	94
Thermally Oxidized (677°C) (5 min.)	92
Thermally Oxidized (760°C) (1 min.)	82
Thermally Oxidized (760°C) (5 min.)	42

Types of Corrosion

Titanium, like any other metal, is subject to corrosion in some environments. The types of corrosion that have been observed on titanium may be classified under the general headings: general corrosion, crevice corrosion, stress corrosion cracking, anodic breakdown pitting, hydriding and galvanic corrosion.

In any contemplated application of titanium, its susceptibility to corrosion by any of these modes should be considered. In order to understand the advantages and limitations of titanium, each of these types of corrosion will be explained.

General Corrosion

General corrosion is characterized by a uniform attack over the entire exposed surface of the metal. The severity of this type of attack can be expressed by a corrosion rate. This type of corrosion is most frequently encountered in hot reducing acid solutions.

Oxidizing agents and certain multi-valent metal ions have the ability to passivate titanium in environments where the metal may be subject to general corrosion. Many process streams, particularly H_2SO_4 and HCl solutions, contain enough impurities in the form of ferric, cupric ions, etc., to passivate titanium and give trouble-free service. In some cases, it may be possible to inhibit corrosion by the addition of suitable passivating agents.

Anodic protection has proven to be quite effective in suppressing corrosion of titanium in many acid solutions. Almost complete passivity can be maintained at almost any acid concentration by the proper application of a small anodic potential. Table 29⁽⁴⁷⁾ gives data showing the passivation achieved in some typical environments.

This procedure is most often employed in acid solutions having a high breakdown potential such as sulfates and phosphates. In halides and some other media, there is a danger of exceeding the breakdown potential which can result in severe pitting. The method is only effective in the area immersed in the solution. It will not prevent attack in the vapor phase.

If the use of passivating agents or anodic protection is not feasible, **TIMETAL® Code-12** or **50A Pd** may solve the problem since these alloys are much more corrosion resistant than the commercially pure grades.

Crevice Corrosion

This is a localized type of attack that occurs only in tight crevices. The crevice may be the result of a structural feature such as a flange or gasket, or it may be caused by the buildup of scales or deposits. Figure 15 shows a typical example of crevice corrosion under a deposit.

Table 29 – Potentials for Anodic Passivation of Unalloyed Titanium

Acid	Applied Potential Volts (H ₂)	Corrosion Rate mpy (mm/y)	Reduction of Corrosion Rate
40% Sulphuric ⁽¹⁾	2.1	0.2 (0.005)	11,000X
37% Hydrochloric ⁽¹⁾	1.7	2.7 (0.068)	2,080X
60% Phosphoric ⁽¹⁾	2.7	0.7 (0.018)	307X
50% Formic ⁽²⁾	1.4	3.3 (0.083)	70X
25% Oxalic ⁽³⁾	1.6	9.8 (0.250)	350X
20% Sulphamic ⁽¹⁾	0.7	0.2 (0.005)	2,710X

⁽¹⁾ 60 C
⁽²⁾ B.P.
⁽³⁾ 90 C

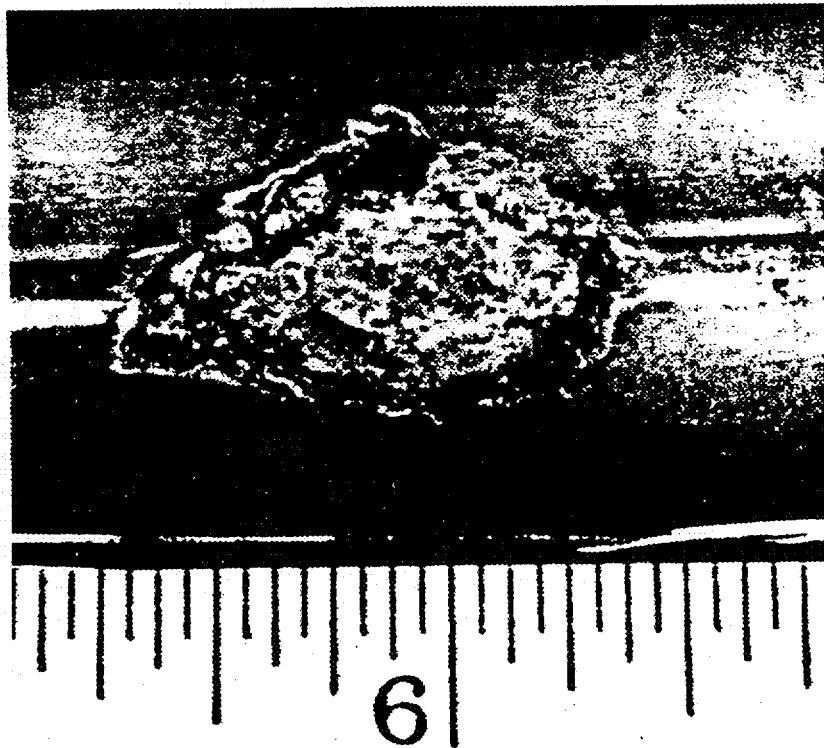


Figure 15 – Crevice Corrosion Under Deposit

Dissolved oxygen or other oxidizing species present in the solution are depleted in the restricted volume of solution in the crevice. These species are consumed faster than they can be replenished by diffusion from the bulk solution.⁴⁴ As a result, the potential of the metal in the crevice becomes more negative than the potential of the metal exposed to the bulk solution. This sets up an electrolytic cell with the metal in the crevice acting as the anode and the metal outside the crevice acting as the cathode as shown in Figure 16.⁴⁸ Metal dissolves at the anode under the influence of the resulting current. Titanium chlorides formed in the crevice are unstable and tend to hydrolyze, forming small amounts of HCl. This reaction is very slow at first, but in the very restricted volume of the crevice, it can reduce the pH of the solution to values as low as 1. This reduces the potential still further until corrosion becomes quite severe.

Although crevice corrosion of titanium is most often observed in hot chloride solutions, it has also been observed in iodide, bromide, fluoride and sulfate solutions.⁴⁴

The presence of small amounts of multi-valent ions in the crevice of such metals as nickel, copper or molybdenum, which act as cathodic depolarizers, tends to drive the corrosion potential of the titanium in the crevice in the positive direction. This counteracts the effect of oxygen depletion and low pH and effectively prevents crevice corrosion. Gaskets impregnated with oxides of these metals have proven to be quite effective in suppressing crevice corrosion.

Alloying with elements such as nickel,

molybdenum, or palladium is also an effective means of overcoming crevice corrosion problems. This is demonstrated by the performance of **TIMETAL® Code-12** and **50A Pd** alloys which are much more resistant to crevice corrosion than commercially pure grades.

Stress Corrosion Cracking (SCC)

This mode of corrosion is characterized by cracking under stress in certain environments. Titanium is subject to this form of corrosion in only a few environments such as red fuming nitric acid, nitrogen tetroxide and absolute methanol.⁵⁰ In most cases, the addition of a small amount of water will serve to passivate the titanium.⁵¹ Titanium is not recommended for use in these environments under anhydrous conditions.

The **TIMETAL® 6-4** alloy is subject to SCC in chloride environments under some circumstances. **TIMETAL® 35A** and **50A** appear to be immune to chloride SCC.

Anodic Breakdown Pitting

This type of corrosion is highly localized and can cause extensive damage to equipment in a very short time. Pitting occurs when the potential of the metal exceeds the breakdown potential of the protective oxide film on the titanium surface.⁵² Fortunately, the breakdown potential of titanium is very high in most environments so that this mode of failure is not common. The breakdown potential in sulfate and phosphate environments is in the 100 volt range. In chlorides it is about 8 to 10 volts, but in bromides and iodides it may be as low as 1 volt.

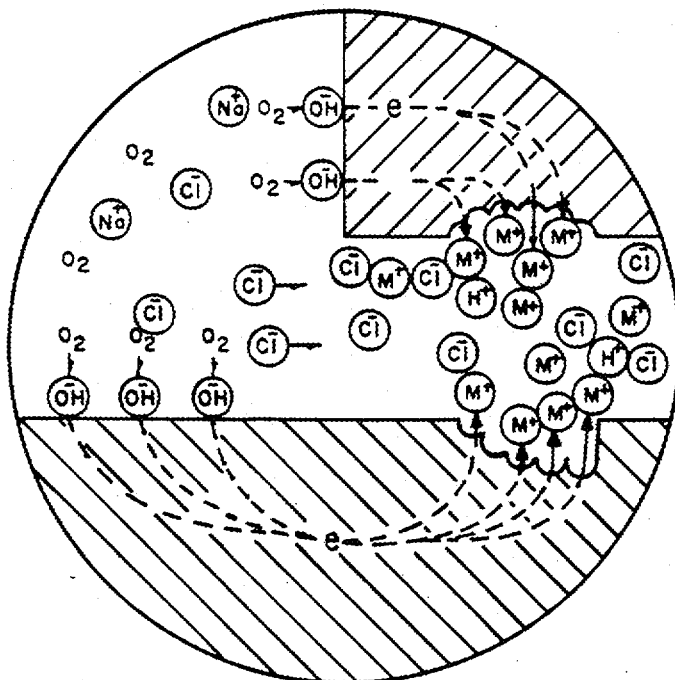


Figure 16 - Schematic Diagram of a Crevice Corrosion Cell.⁴⁸

Increasing temperature and acidity tend to lower the breakdown potential so that under some extreme conditions the potential of the metal may equal or exceed the breakdown potential and spontaneous pitting will occur. This type of corrosion is most frequently encountered in applications where an anodic potential exceeding the breakdown potential is impressed on the metal. An example is shown in Figure 17. This is a close-up view of the side plate of a titanium anode basket used in a zinc plating cell. It was a chloride electrolyte and the cell was operated at 10 volts which is about 1-2 volts above the breakdown potential for titanium in this environment. Extensive pitting completely destroyed the basket.

This type of pitting is sometimes caused inadvertently by improper grounding of equipment during welding or other operations that can produce an anodic potential on the titanium.

This type of corrosion can be avoided in most instances by making certain that no impressed anodic currents approaching the breakdown potential are applied to the equipment.

Another type of pitting failure that is sometimes encountered in commercially pure titanium is shown in Figure 18. The specimen in Figure 18 showed scratch marks which gave indications of iron when examined with an electronprobe. It is believed the pits initiated at points where iron has been smeared into the titanium surface until it penetrated the TiO_2 protective film.

Potential measurements on mild steel and unalloyed titanium immersed in a saturated brine solution at temperatures near the boiling point gave a potential difference of nearly 0.5 volt. This is sufficient to establish an electrochemical cell in which the iron would be consumed as the anode. By the time the iron is consumed, a pit has started to grow in which acid conditions develop preventing the formation of a passive film and the reaction continues until the tube is perforated.⁽⁵³⁾

This type of pitting appears to be a high temperature phenomenon. It has not been known to occur below 170°F (77°C). It has not been induced on **TIMETAL® Code-12** or **50A Pd** in laboratory tests. These two alloys are believed to be highly resistant to this type of attack. However, precautions should be taken with all titanium alloys to remove or avoid surface iron contamination, if the application involves temperatures in excess of 170°F (77°C).



Figure 17 – Anodic Breakdown Pitting of Titanium



Figure 18 – Unalloyed Titanium Tube which has been Perforated by Pitting in Hot Brine.

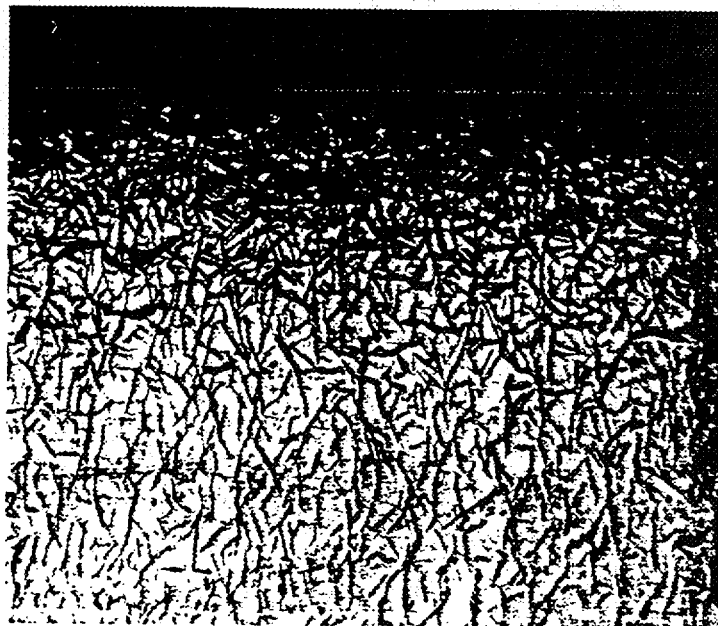


Figure 19 - Hydrided Titanium

The most effective means of removing surface iron contamination is to clean the titanium surface by immersion in 35% HNO_3 —5% HF solution for two to five minutes followed by a water rinse.

Hydrogen Embrittlement

Titanium is being widely used in hydrogen-containing environments and under conditions where galvanic couples or cathodic protection systems cause hydrogen to be evolved on the surface of titanium. In most instances, no problems have been reported. However, there have been some equipment failures in which embrittlement by hydride formation was implicated.

An example of a hydrided titanium tube is shown in Figure 19. This is a photomicrograph of a cross section of the tube wall. The brown-black needle-like formations are hydrides. Note the heavy concentration at the top which indicates the hydrogen entered from the external surface.

The oxide film which covers the surface of titanium is a very effective barrier to hydrogen penetration, however, titanium can absorb hydrogen from hydrogen containing environments under some circumstances.

At temperatures below 176°F (80°C) hydriding occurs so slowly that it has no practical significance, except in cases where severe tensile stresses are present. In the presence of pure anhydrous hydrogen gas, at elevated temperatures and pressures, severe hydriding of titanium can be expected. Titanium is not recommended for use in pure hydrogen because of the possibility of hydriding if the oxide film is broken. Laboratory tests, however, have shown that the presence of as little as 2% moisture in hydrogen gas effec-

tively passivates titanium so that hydrogen absorption does not occur even at pressures as high as 800 psi and temperatures to 315°F (157°C). It is believed that the moisture serves as a source of oxygen to keep the protective oxide film in a good state of repair. Titanium is being used extensively with very few problems in oil refineries in many applications where the process streams contain hydrogen.

A more serious problem occurs when cathodically impressed or galvanically induced currents generate atomic hydrogen directly on the surface of titanium. The presence of moisture does not inhibit hydrogen absorption of this type.⁽³⁸⁾

Laboratory investigations and experience have demonstrated that three conditions usually exist simultaneously for hydriding of unalloyed titanium to occur:

1. The pH of the solution is less than 3 or greater than 12; the metal surface must be damaged by abrasion; or impressed potentials are more negative than -0.70V .⁽³⁹⁾
2. The temperature is above 176°F (80°C) or only surface hydride films will form, which experience indicates do not seriously affect the properties of the metal. Failures due to hydriding are rarely encountered below this temperature.⁽³⁷⁾ (There is some evidence that severe tensile stresses may promote diffusion at low temperatures.)
3. There must be some mechanism for generating hydrogen. This may be a galvanic couple, cathodic protection by impressed current, corrosion of titanium, or dynamic abrasion of the surface with sufficient intensity to depress the metal potential below that required for spontaneous evolution of hydrogen.

Table 30 – Galvanic Series in Flowing Water
(13 ft. sec. at about 75°F (23.9°C))¹¹

Material	Steady State Electrode Potential, Volts (Saturated Calomel Half-Cell)
Graphite	+ 0.25
Platinum	+ 0.15
Zirconium	- 0.04
Type 316 Stainless Steel (Passive)	- 0.05
Type 304 Stainless Steel (Passive)	- 0.08
Monel 400	- 0.08
Hastelloy C	- 0.08
Titanium	- 0.10
Silver	- 0.13
Type 410 Stainless Steel (Passive)	- 0.15
Type 316 Stainless Steel (Active)	- 0.18
Nickel	- 0.20
Type 430 Stainless Steel (Passive)	- 0.22
Copper Alloy 715 (70-30 Cupro-Nickel)	- 0.25
Copper Alloy 706 (90-10 Cupro-Nickel)	- 0.28
Copper Alloy 442 (Admiralty Brass)	- 0.29
G Bronze	- 0.31
Copper Alloy 687 (Aluminum Brass)	- 0.32
Copper	- 0.36
Alloy 464 (Naval Rolled Brass)	- 0.40
Type 410 Stainless Steel (Active)	- 0.52
Type 304 Stainless Steel (Active)	- 0.53
Type 430 Stainless Steel (Active)	- 0.57
Carbon Steel	- 0.61
Cast Iron	- 0.61
Aluminum 3003-H	- 0.79
Zinc	- 1.03

Most of the hydriding failures of titanium that have occurred in service can be explained on this basis.⁽³⁸⁾ Hydriding can usually be avoided by altering at least one of the three conditions listed above. Note that accelerated hydrogen absorption of titanium at very high cathodic current densities (more negative than -1.0V SCE) in ambient temperature seawater represents one exception to this rule.

Galvanic Corrosion

The coupling of titanium with dissimilar metals usually does not accelerate the corrosion of the titanium. The exception is in reducing environments where titanium does not passivate. Under these conditions, it has a potential similar to aluminum and will undergo accelerated corrosion when coupled to other more noble metals.

Table 30 gives the galvanic series in seawater. In this environment, titanium is passive and exhibits a potential of about -0.1 V versus a saturated calomel reference cell (11) which places it high on the passive or noble end of the series.

For most environments, titanium will be the cathodic member of any galvanic couple. It may accelerate the corrosion of the other member of the couple, but in most cases, the titanium will be unaffected. Figure 20 shows the accelerating effect that titanium has on the corrosion rate of various metals when they are galvanically connected in seawater. If the area of the titanium exposed is small in relation to the area of the other metal, the effect on the corrosion rate is negligible. However, if the area of the titanium (cathode) greatly exceeds the area of the other metal (anode) severe corrosion may result.

Because titanium is usually the cathodic member of any galvanic couple, hydrogen will be evolved on its surface proportional to the galvanic current flow. This may result in the formation of surface hydride films that are generally stable and cause no problems. If the temperature is above 170°F (77°C), however, hydriding can cause embrittlement.

In order to avoid problems with galvanic corrosion, it is best to construct equipment of a single metal. If this is not practical, use two metals that are close together in the galvanic series, insulate the joint or cathodically protect the less noble metal. If dissimilar metals are necessary, construct the critical parts out of titanium, since it is usually not attacked, and use large areas of the less noble metal and heavy sections to allow for increased corrosion.

- 1 - Low carbon steel
- 2 - Gunmetal (88/10/2)
- 3 - Aluminum
- 4 - 70 Cu - 30 Ni
- 5 - 80 Cu - 20 Ni
- 6 - Monel (67/31/1/1)
- 7 - Aluminum Bronze 614
- 8 - 60/40 Brass (Muntz Metal)
- 9 - Aluminum brass (Alloy 687)
- 10 - 18/8 Stainless (304)

2500 hour in seawater

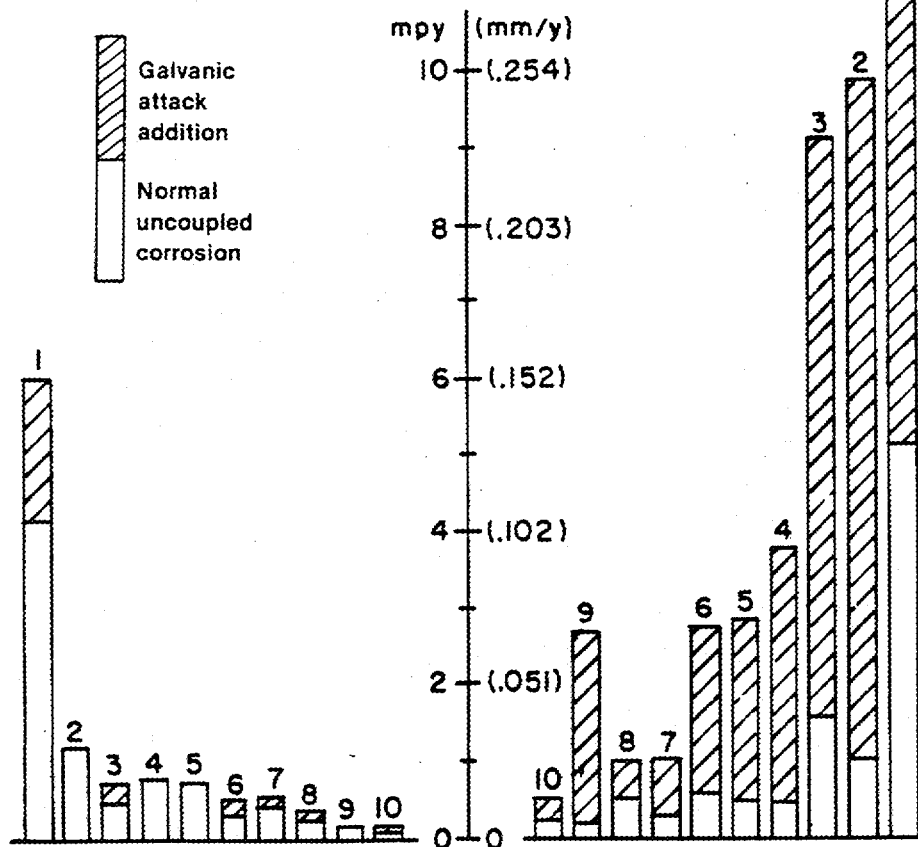
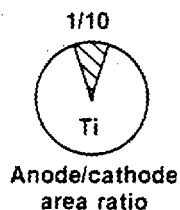
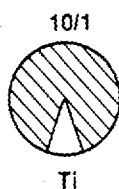


Figure 20 - The Dissimilar Metals Problem.⁽¹¹⁾

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Appendix

Titanium Corrosion Rate Data — TIMETAL® Commercially Pure Grades

These data were determined in laboratory tests and are intended only as a guide. Since service conditions may be dissimilar, TIMET recommends testing under the anticipated operating conditions.

C = Concentration %

T = Temperature °F (°C)

R = Corrosion rate, mpy (mm/y)

MEDIA	C	T	R	MEDIA	C	T	R
Acetaldehyde	75	300 (149)	0.02 (0.001)	Barium chloride	5	212 (100)	nil
	100	300 (149)	nil	Barium chloride	20	212 (100)	0.01 (0.000)
Acetate, n-propyl	—	188 (87)	nil	Barium chloride	25	212 (100)	nil
Acetic acid	5 to 99.7	255 (124)	nil	Barium hydroxide	saturated	room	nil
	33-vapor	boiling	nil	Barium hydroxide	27	boiling	some small pits
	65	250 (121)	0.1 (0.003)	Barium nitrate	10	room	nil
	58	266 (130)	15.0 (0.381)	Barium fluoride	saturated	room	nil
Acetic acid	99.7	255 (124)	0.1 (0.003)	Benzaldehyde	100	room	nil
Acetic acid +	31.2	boiling	10.2 (0.259)	Benzene (traces of HCl)	vapor & liquid	176 (80)	0.2 (0.005)
109 ppm Cl				Benzene (traces of HCl)	liquid	122 (50)	1.0 (0.025)
Acetic acid +	62.0	boiling	10.7 (0.272)	Benzene	liquid	room	nil
106 ppm Cl				Benzene + trace HCl, NaCl and CS ₂	—	176 (80)	0.2 (0.005)
Acetic anhydride	99.5	boiling	0.5 (0.013)	Benzoic acid	saturated	room	nil
Acidic gases	—	100-500 (38-260)	<1.0 (<0.025)	Bismuth	molten	1500 (816)	high
containing CO ₂ , H ₂ O, Cl ₂ , SO ₂ , SO ₃ , H ₂ S, O ₂ , NH ₃				Bismuth/lead	molten	572 (300)	good resistance
Adipic acid + 15-20% glutaric + 2% acetic acid	25	390 (199)	nil	Boric acid	saturated	room	nil
Adipic acid	67	450 (232)	nil	Boric acid	10	boiling	nil
Adipyl chloride (acid chlorobenzene solution)	—	—	nil	Bromine	liquid	86 (30)	rapid
Adiponitrile	vapor	700 (371)	0.3 (0.008)	Bromine, moist	vapor	86 (30)	<0.1 (<0.003)
Aluminum chloride, aerated	10	212 (100)	0.09 (0.002)*	Bromine, gas dry	—	70 (21)	dissolves rapidly
Aluminum chloride, aerated	25	212 (100)	124 (3.15)*	Bromine - water solution	—	room	nil
Aluminum chloride, non-aerated	10	302 (150)	1.3 (0.033)*	Bromine-methyl alcohol solution	500 ppm	140 (60)	1.2 (0.030) some cracking
	25	212 (100)	258 (6.55)*	Bromine in methyl alcohol	5	—	757 (19.2)
Aluminum	molten	1250 (677)	6480 (164.6)	N-butyric acid	undiluted	room	nil
Aluminum fluoride	saturated	room	nil	Calcium bisulfite	cooking liquor	79 (26)	0.02 (0.001)
Aluminum nitrate	saturated	room	nil	Calcium carbonate	saturated	boiling	nil
Aluminum sulfate	saturated	room	nil	Calcium chloride	5	212 (100)	0.02 (0.005)*
Aluminum sulfate + 1% H ₂ SO ₄	saturated	room	nil	Calcium chloride	10	212 (100)	0.29 (0.007)*
Amines, synthesis of organic	—	300-400 (149-204)	15 (0.381)	Calcium chloride	20	212 (100)	0.61 (0.015)*
Ammonium acid phosphate	10	room	nil	Calcium chloride	55	220 (104)	0.02 (0.001)*
Ammonium aluminum chloride	molten	662-716 (350-380)	very rapid	Calcium chloride	60	300 (149)	<0.1 (<0.003)*
Ammonia anhydrous	100	104 (40)	<5.0 (<0.127)	Calcium chloride	62	310 (154)	2.0 and 16 (0.051 and 0.406)*
Ammonia, steam, water	—	431 (222)	440 (11.2)	Calcium chloride	73	350 (177)	84 (2.13)*
Ammonium acetate	10	room	nil	Calcium hydroxide	saturated	room	nil
Ammonium bicarbonate	50	212 (100)	nil	Calcium hypochlorite	saturated	boiling	nil
Ammonium bisulfite, spent pulping liquor	159 (71)	0.6 (0.015)		Calcium hypochlorite	2	212 (100)	0.05 (0.001)
Ammonium carbamate	50	212 (100)	nil	Calcium hypochlorite	6	212 (100)	0.05 (0.001)
Ammonium chloride	saturated	212 (100)	<0.5 (<0.013)	Calcium hypochlorite	18	70 (21)	nil
Ammonium chlorate (+ 215-250 g/l NaCl) (+ 36 g/l NaClO ₄)	300 g/l	122 (50)	0.1 (0.003)	Calcium hypochlorite	saturated slurry	—	nil
Ammonium fluoride	10	room	4.0 (0.102)	Carbon dioxide	100	—	excellent
Ammonium hydroxide	28	room	0.1 (0.003)	Carbon tetrachloride	99	boiling	0.18 (0.005)
Ammonium nitrate	28	boiling	nil	Carbon tetrachloride	liquid	boiling	nil
Ammonium nitrate + 1% nitric acid	28	boiling	nil	Carbon tetrachloride	vapor	boiling	nil
Ammonium oxalate	saturated	room	nil	Chlorine gas, wet	>0.7 H ₂ O	room	nil
Ammonium perchlorate	20	190 (88)	nil	Chlorine gas, wet	>0.95 H ₂ O	284 (140)	nil
Ammonium sulfate	10	212 (100)	nil	Chlorine gas, wet	>1.5 H ₂ O	392 (200)	nil
Ammonium sulfate + 1% H ₂ SO ₄	saturated	room	0.4 (0.010)	Chlorine gas, wet	liquid water on surface	room	nil
Aniline	100	room	nil	Chlorine saturated water	saturated	207 (97)	nil
Aniline + 2% AlCl ₃	98	316 (158)	>50 (>1.27)	Chlorine header sludge and wet chlorine	—	207 (97)	0.03 (0.001)
Aniline + 2% AlCl ₃	98	600 (316)	840 (21.3)	Chlorine gas, dry	<0.5 H ₂ O	room	may react
Aniline hydrochloride	5	212 (100)	nil	Chlorine dioxide	5 in steam gas + H ₂ O and air	180 (82)	<0.1 (<0.003)
Aniline hydrochloride	20	212 (100)	nil	Chlorine dioxide	15 + some HOCl and wet Cl ₂	110 (43)	nil
Antimony trichloride	27	room	nil	Chlorine dioxide	5	210 (99)	nil
Aqua regia	3:1	room	nil	Chlorine monoxide	up to 15 + some HOCl, Cl ₂ & H ₂ O	110 (43)	nil
Aqua regia	3:1	175 (79)	34.8 (0.884)				
Arsenous oxide	saturated	room	nil				
Barium carbonate	saturated	room	nil				

Appendix

Titanium Corrosion Rate Data — **TIMETAL®** Commercially Pure Grades

These data were determined in laboratory tests and are intended only as a guide. Since service conditions may be dissimilar, TIMET recommends testing under the anticipated operating conditions.

C = Concentration %

T = Temperature °F (°C)

R = Corrosion rate, mpy (mm/y)

MEDIA	C	T	R	MEDIA	C	T	R
Chlorine trifluoride	100	<86 (30)	vigorous reaction	Formic acid, non-aerated	10	212 (100)	>50 (>1.27)**
Chloroacetic acid	30	180 (82)	<5.0 (<0.127)	Formic acid, non-aerated	25	212 (100)	96 (2.44)**
Chloroacetic acid	100	boiling	<5.0 (<0.127)	Formic acid, non-aerated	50	boiling	126 (3.20)**
Chlorosulfonic acid	100	room	7.5-12.3 (0.191-0.312)	Formic acid, non-aerated	90	212 (100)	118 (3.00)**
Chloroform	vapor & liquid	boiling	0.01 (0.000)	Formic acid	9	122 (50)	<5 (<0.127)
Chloropicrin	100	203 (95)	0.1 (0.003)	Furfural	100	room	nil
Chromic acid	10	boiling	0.1 (0.003)	Gluconic acid	50	room	nil
Chromic acid	15	75 (24)	0.2 (0.006)	Glycerin	—	room	nil
Chromic acid	15	180 (82)	0.6 (0.015)	Hydrogen chloride, gas	air mixture	ambient	nil
Chromic acid	50	75 (24)	0.5 (0.013)	Hydrochloric acid, aerated	5	95 (35)	1.5 (0.038)
Chromic acid	50	180 (82)	1.1 (0.028)	Hydrochloric acid, aerated	10	95 (35)	40 (1.02)
Chromium plating bath containing fluoride	240 g/l plating salt	171 (77)	58.3 (1.48)	Hydrochloric acid, aerated	20	95 (35)	175 (4.45)
Chromic acid + 5% nitric acid	5	70 (21)	<0.1 (<0.003)	Hydrochloric acid, aerated	37.5	95 (35)	1990 (50.6)
Citric acid	10	212 (100)	0.36 (0.009)	Hydrochloric acid	1	boiling	>100 (>2.54)
Citric acid	25	212 (100)	0.03 (0.001)	Hydrochloric acid	3	boiling	550 (14.0)
Citric acid	50	140 (60)	0.01 (0.000)	Hydrochloric acid	5	boiling	400 (10.2)
Citric acid	50	212 (100)	<5.0 (<0.127)	Hydrochloric acid, nitrogen saturated	3	374 (190)	>1120 (>28.5)
Citric acid, aerated	50	boiling	5-50 (0.127-1.27)	Hydrochloric acid, nitrogen saturated	5	374 (190)	>1120 (>28.5)
Citric acid	62	300 (149)	corroded	Hydrochloric acid, nitrogen saturated	10	374 (190)	>1120 (>28.5)
Copper nitrate	saturated	room	nil	Hydrochloric acid, oxygen saturated	3	374 (190)	>1120 (>28.5)
Copper sulfate	50	boiling	nil	Hydrochloric acid, oxygen saturated	5	374 (190)	>1120 (>28.5)
Copper sulfate + 2% H ₂ SO ₄	saturated	room	0.7 (0.018)	Hydrochloric acid, chlorine saturated	5	374 (190)	<1 (<0.025)
Cupric carbonate + cupric hydroxide	saturated	ambient	nil	Hydrochloric acid, chlorine saturated	10	374 (190)	>1120 (>28.5)
Cupric chloride	20	boiling	nil	Hydrochloric acid, 200 ppm Cl ₂	36	room	17.0 (0.432)
Cupric chloride	40	boiling	0.2 (0.005)	Hydrochloric acid, + 1% HNO ₃	5	100 (38)	nil
Cupric chloride	55	246 (119) (boiling)	0.1 (0.003)	Hydrochloric acid, + 1% HNO ₃	5	200 (93)	3.6 (0.091)
Cupric cyanide	saturated	room	nil	Hydrochloric acid, + 5% HNO ₃	5	100 (38)	0.84 (0.025)
Cuprous chloride	50	194 (90)	<0.1 (<0.003)	Hydrochloric acid, + 5% HNO ₃	5	200 (93)	1.2 (0.030)
Cyclohexylamine	100	room	nil	Hydrochloric acid, + 10% HNO ₃	5	100 (38)	nil
Cyclohexane (plus traces of formic acid)	—	302 (150)	0.1 (0.003)	Hydrochloric acid, + 10% HNO ₃	5	200 (93)	7.2 (0.183)
Dichloroacetic acid	100	212 (100)	<0.5 (<0.013)	Hydrochloric acid, + 3% HNO ₃	8.5	176 (80)	2.0 (0.051)
Dichloroacetic acid	100	boiling	0.29 (0.007)	Hydrochloric acid, + 5% HNO ₃	1	boiling	2.9 (0.074)
Dichlorobenzene + 4-5% HCl	—	355 (179)	4 (0.102)	Hydrochloric acid, + 5% HNO ₃ + 1.7 g/l TiCl ₄	1	boiling	nil
Diethylene triamine	100	room	nil	Hydrochloric acid, + 2.5% NaClO ₃	10.2	176 (80)	0.37 (0.009)
Ethyl alcohol	95	boiling	0.5 (0.013)	Hydrochloric acid, + 5.0% NaClO ₃	10.2	175 (79)	0.25 (0.006)
Ethyl alcohol	100	room	nil	Hydrochloric acid, + 0.5% CrO ₃	5	100 (38)	nil
Ethylene dichloride	100	boiling	0.2-5.0 (0.005-0.127)	Hydrochloric acid, + 0.5% CrO ₃	5	200 (93)	1.2 (0.031)
Ethylene diamine	100	room	nil	Hydrochloric acid, + 1% CrO ₃	5	100 (38)	0.72 (0.018)
Ferric chloride	10-20	room	nil	Hydrochloric acid, + 1% CrO ₃	5	200 (93)	1.2 (0.031)
Ferric chloride	10-30	212 (100)	<0.5 (<0.127)	Hydrochloric acid, + 0.05% CuSO ₄	5	100 (38)	1.56 (0.040)
Ferric chloride	10-40	boiling	nil	Hydrochloric acid, + 0.05% CuSO ₄	5	200 (93)	3.6 (0.091)
Ferric chloride	50	236 (113) (boiling)	nil	Hydrochloric acid, + 0.5% CuSO ₄	5	100 (38)	3.6 (0.091)
Ferric chloride	50	302 (150)	0.1 (0.003)	Hydrochloric acid, + 0.5% CuSO ₄	5	200 (93)	2.4 (0.061)
Ferric sulfate-9 H ₂ O	10	room	nil	Hydrochloric acid, + 1% CuSO ₄	5	100 (38)	1.2 (0.031)
Ferrous chloride + 0.5% HCl + 3% resorcinol pH 1	30	175 (79)	0.2 (0.006)	Hydrochloric acid, + 1% CuSO ₄	5	200 (93)	3.6 (0.091)
Ferrous sulfate	saturated	room	nil	Hydrochloric acid, + 5% CuSO ₄	5	100 (38)	0.8 (0.020)
Fluoroboric acid	5-20	elevated	rapid	Hydrochloric acid, + 5% CuSO ₄	5	200 (93)	2.4 (0.061)
Fluorine, commercial	gas-liquid alternated	gas-109 liquid (43) -320 (-196)	18-34 (0.457-0.864)	Hydrochloric acid, + 0.05% CuSO ₄	5	boiling	2.5 (0.064)
Fluorine, HF free	12 liquid 12 gas	-320 (-196)	0.08 (0.002)	Hydrochloric acid, + 0.5% CuSO ₄	5	boiling	3.3 (0.084)
Fluorine, HF free	liquid	-320 (-196)	<0.43 (0.011)	Hydrochloric acid, + 0.05% CuSO ₄	10	150 (66)	0.68-1.32 (0.017-0.025)
Fluorine, HF free	gas	-320 (-196)	0.42 (0.011)	Hydrochloric acid, + 0.20% CuSO ₄	10	150 (66)	nil
Fluorosilicic acid	10	room	1870 (47.5)	Hydrochloric acid, + 0.5% CuSO ₄	10	150 (66)	nil-0.68 (0.023)
Food products	—	ambient	no attack	Hydrochloric acid, + 1% CuSO ₄	10	150 (66)	0.68 (0.023)
Formaldehyde	37	boiling	nil	Hydrochloric acid, + 0.05% CuSO ₄	10	boiling	11.6 (0.295)
Formamide vapor	—	572 (300)	nil	Hydrochloric acid, + 0.5% CuSO ₄	10	boiling	11.4 (0.290)
Formic acid, aerated	10	212 (100)	0.18 (0.005)**	Hydrochloric acid, + 0.2% CuSO ₄ + 0.2% organic amine	10	boiling	9.0 (0.229)
Formic acid, aerated	25	212 (100)	0.04 (0.001)**				
Formic acid, aerated	50	212 (100)	0.04 (0.001)**				
Formic acid, aerated	90	212 (100)	0.05 (0.001)**				

** TIMETAL® Code-12 and 50A Pd immune

Appendix

Titanium Corrosion Rate Data — TIMETAL® Commercially Pure Grades

These data were determined in laboratory tests and are intended only as a guide. Since service conditions may be dissimilar, TIMET recommends testing under the anticipated operating conditions.

C = Concentration %

T = Temperature F (°C)

R = Corrosion rate, mpy (mm y)

MEDIA	C	T	R
Hydrofluoric acid	1.48	room	rapid
Hydrofluoric acid, anhydrous	100	room	5.0-50 (0.127-1.27)
Hydrofluoric-nitric acid	1-HF -15HNO ₃	room	rapid
Hydrogen peroxide	3	room	<5 (<0.127)
Hydrogen peroxide	6	room	<5 (<0.127)
Hydrogen peroxide	30	room	<12 (<0.305)
Hydrogen sulfide, steam and 0.077% mercaptans	7.65	200-230 (93-110)	nil
Hydroxy-acetic acid	-	104 (40)	1.2 (0.031)
Hypochlorous acid + Cl ₂ O and Cl ₂ gases	17	100 (38)	0.001 (0.000)
Iodine, dry gas	-	70 (21)	<4 (<0.102)
Iodine in water + potassium iodide	-	room	nil
Iodine in alcohol	saturated	room	pitted
Lactic acid	10-85	212 (100)	<5.0 (<0.127)
Lactic acid	10	boiling	<5.0 (<0.127)
Lead	-	1500 (816)	attacked
Lead	-	615-1100 (324-593)	good
Lead acetate	saturated	room	nil
Linseed oil, boiled	-	room	nil
Lithium, molten	-	600-900 (316-482)	nil
Lithium chloride	50	300 (149)	nil
Magnesium	molten	1400 (760)	limited resistance
Magnesium chloride	5-20	212 (100)	<0.4 (<0.010)*
Magnesium chloride	5-40	boiling	nil
Magnesium hydroxide	saturated	room	nil
Magnesium sulfate	saturated	room	nil
Manganous chloride	5-20	212 (100)	nil
Maleic acid	18-20	95 (35)	.06 (0.002)
Mercuric chloride	1	212 (100)	0.01 (0.000)
Mercuric chloride	5	212 (100)	0.42 (0.011)
Mercuric chloride	10	212 (100)	0.04 (0.001)
Mercuric chloride	saturated	212 (100)	<5 (<0.127)
Mercuric cyanide	saturated	room	nil
Mercury	100	up to 100 (38)	satisfactory
Mercury	100	room	nil
Mercury	-	700 (371)	119.4 (3.03)
Methyl alcohol	91	95 (35)	nil
Mercury + Fe	-	700 (371)	3.12 (0.079)
Mercury + Cu	-	700 (371)	2.48 (0.063)
Mercury + Zr	-	700 (371)	1.28 (0.033)
Mercury + Mg	-	700 (371)	3.26 (0.083)
Nickel chloride	5	212 (100)	0.17 (0.004)
Nickel chloride	20	212 (100)	0.11 (0.003)
Nickel nitrate-6H ₂ O	50	room	nil
Nitric acid, aerated	10	room	0.19 (0.005)
Nitric acid, aerated	20	room	9.69 (0.246)
Nitric acid, aerated	30	room	0.17 (0.004)
Nitric acid, aerated	40	room	0.08 (0.002)
Nitric acid, aerated	50	room	0.08 (0.002)
Nitric acid, aerated	60	room	0.02 (0.001)
Nitric acid, aerated	70	room	0.18 (0.005)
Nitric acid, aerated	10	104 (40)	0.10 (0.003)
Nitric acid, aerated	20	104 (40)	0.21 (0.005)
Nitric acid, aerated	30	122 (50)	0.61 (0.015)
Nitric acid, aerated	40	122 (50)	0.64 (0.016)
Nitric acid, aerated	50	140 (60)	1.46 (0.037)
Nitric acid, aerated	60	140 (60)	1.56 (0.040)
Nitric acid, aerated	70	158 (70)	1.56 (0.040)
Nitric acid, aerated	40	392 (200)	24 (0.610)
Nitric acid, aerated	70	518 (270)	48 (1.22)
Nitric acid, aerated	20	554 (290)	12 (0.305)
Nitric acid, non-aerated	35	176 (80)	2-4 (0.051-0.102)
Nitric acid, non-aerated	70	176 (80)	1-3 (0.025-0.076)
Nitric acid	17	boiling	3-4 (0.076-0.102)
Nitric acid	35	boiling	5-20 (0.127-0.508)
Nitric acid	70	boiling	2.5-37 (0.064-0.940)

MEDIA	C	T	R
Nitric acid, white fuming	-	room	0.1 (0.003)
Nitric acid, white fuming	liquid or vapor	room	nil
Nitric acid, white fuming	-	180 (82)	6.0 (0.152)
Nitric acid, white fuming	-	252 (122)	<5.0 (<0.127)
Nitric acid, white fuming	-	320 (160)	<5.0 (<0.127)
Nitric acid, red fuming	<about 2% H ₂ O	room	ignition sensitive
Nitric acid, red fuming	>about 2% H ₂ O	room	not ignition sensitive
Nitric acid + 0.1% CrO ₃	40	boiling	0.12-0.99 (0.003-0.025)
Nitric acid + 10% FeCl ₃	40	boiling	4.8-7.4 (0.122-0.188)
Nitric acid + 0.1% K ₂ Cr ₂ O ₇	40	boiling	nil-0.62 (nil-0.016)
Nitric acid + 10% NaClO ₃	33-45	boiling	0.12-1.40 (0.003-0.036)
Nitric acid, saturated with zirconyl nitrate	65	245 (118)	nil
Nitric acid + 15% zirconyl nitrate	20.8	boiling	5-11.6 (0.127-0.295)
Nitric acid + 179 g/l NaNO ₃ and 32 g/l NaCl	27.4	boiling	19-115 (0.483-2.92)
Nitric acid + 170 g/l NaNO ₃ and 2.9 g/l NaCl	-	ambient	0.26-23.2 (0.007-0.589)
Oil well crudes, varying amounts of abrasion	1	98.6 (37)	12 (0.025)
Oxalic acid	1	boiling	4247 (107.9)
Oxalic acid	25	140 (60)	470 (11.9)
Oxalic acid	saturated	room	20 (0.508)
Perchloryl fluoride + liquid ClO ₃	100	86 (30)	0.07 (0.002)
Perchloryl fluoride + 1% H ₂ O	99	86 (30)	liquid 11.4 (0.290) vapor 0.1 (0.003)
Phenol	saturated solution	70 (21)	4.0 (0.102)
Phosphoric acid	10-30	room	0.8-2 (0.020-0.051)
Phosphoric acid	30-80	room	2-30 (0.051-0.762)
Phosphoric acid	1	boiling	10 (0.254)
Phosphoric acid	10	boiling	400 (10.2)
Phosphoric acid	30	boiling	1030 (26.2)
Phosphoric acid	10	176 (80)	72 (1.83)
Phosphoric acid + 3% nitric acid and 16% water	81	190 (88)	15 (0.381)
Phosphorus oxychloride	100	room	0.14 (0.004)
Phosphorus trichloride	saturated	room	nil
Photographic emulsions	-	-	<5.0 (<0.127)
Phthalic acid	saturated	room	nil
Potassium bromide	saturated	room	nil
Potassium chloride	saturated	room	nil
Potassium chloride	saturated	140 (60)	<.01 (0.000)
Potassium dichromate	-	-	nil
Potassium ethyl xanthate	10	room	nil
Potassium ferrocyanide	saturated	room	nil
Potassium hydroxide + 13% potassium chloride	13	85 (29)	nil
Potassium hydroxide	50	80 (29)	0.4 (0.010)
Potassium hydroxide	10	boiling	<5.0 (<0.127)
Potassium hydroxide	25	boiling	12 (0.305)
Potassium hydroxide	50	boiling	108 (2.74)
Potassium hydroxide	50 to anhydrous	465-710 (241-377)	40-60 (1.02-1.52)
Potassium iodide	saturated	room	nil
Potassium permanganate	saturated	room	nil
Potassium perchlorate (Ti specimen cathodic)	20	room	0.12 (0.003)

Appendix

Titanium Corrosion Rate Data — **TIMETAL®** Commercially Pure Grades

These data were determined in laboratory tests and are intended only as a guide. Since service conditions may be dissimilar, TIMET recommends testing under the anticipated operating conditions.

C = Concentration %

T = Temperature °F (°C)

R = Corrosion rate, mpy (mm/y)

MEDIA	C	T	R	MEDIA	C	T	R
Potassium perchlorate, + NaClO ₄ , 600-900 g/l	0-30	122 (50)	0.1 (0.003)	Stannic chloride	saturated	room	nil
KCL, 0-500 g/l				Steam + air	—	180 (82)	0.01 (0.000)
NaCl, 0-250 g/l				Steam + 7.65% hydrogen sulfide + 0.17% mercaptans	—	200-230 (93-110)	nil
NaClO ₃ , 6-24 g/l				Stearic acid, molten	100	356 (180)	0.1 (0.003)
Potassium sulfate	10	room	nil	Succinic acid	100	365 (185)	nil
Potassium thiosulfate	1	—	nil	Succinic acid saturated		room	nil
Propionic acid	vapor	374 (190)	rapid	Sulfamic acid saturated		room	nil
Pyrogalllic acid	355 g/l	room	nil	Sulfamic acid	3.75 g/l	boiling	nil
Salicylic acid	saturated	room	nil	Sulfamic acid	7.5 g/l	boiling	108 (2.74)
sodium salt				Sulfamic acid + 375 g/l FeCl ₃	7.5 g/l	boiling	1.2 (0.030)
Seawater	—	76 (24)	nil	Sulfur, molten	100	464 (240)	nil
Seawater, 4 1/2-year test	—	—	nil	Sulfur monochloride	major	395 (202)	>43 (>1.09)
Sebacic acid	—	464 (240)	0.3 (0.008)	Sulfur dioxide, water	near 100	room	0.1 (0.003)
Silver nitrate	50	room	nil				
Sodium	100	to 1100 (593)	good	Sulfur dioxide gas + small amount SO ₂ and approx. 3% O ₂	18	600 (316)	0.2 (0.006)
Sodium acetate	saturated	room	nil	Sulfuric acid, aerated	1	140 (60)	0.3 (0.008)
Sodium aluminate	25	boiling	3.6 (0.091)	with air	3	140 (60)	0.5 (0.013)
Sodium bifluoride	saturated	room	rapid	Sulfuric acid, aerated	5	140 (60)	190 (4.83)
Sodium bisulfate	saturated	room	nil	with air	10	95 (35)	50 (1.27)
Sodium bisulfate	10	150 (66)	72 (1.83)	Sulfuric acid, aerated	40	95 (35)	340 (8.64)
Sodium bisulfite	10	boiling	nil	with air	75	95 (35)	42 (1.07)
Sodium bisulfite	25	boiling	nil	Sulfuric acid, aerated	75	room	427 (10.8)
Sodium carbonate	25	boiling	nil	with air	75	boiling	6082 (154.5)
Sodium chlorate	saturated	room	nil	Sulfuric acid, aerated	1	212 (100)	0.2 (0.005)
Sodium chlorate + NaCl 80-250 g/l + Na ₂ Cr ₂ O ₇ 14 g/l carbon 0.3-0.9 g/l	0-721 g/l	104 (40)	0.1 (0.003)	with air	3	212 (100)	920 (23.4)
Sodium chloride	saturated	room	nil	Sulfuric acid, aerated	5	212 (100)	810 (20.6)
Sodium chloride pH 1.5	23	boiling	nil*	with air	80	room	316 (8.03)
Sodium chloride pH 1.2	23	boiling	28 (0.711)*	Sulfuric acid, aerated	80	boiling	7460 (189.5)
Sodium chloride, titanium in contact with teflon	23	boiling	Corrosion in crevice	with air	concentrated	room	62 (1.57)
Sodium chloride, pH 1.2 some dissolved chlorine	23	boiling	nil*	Sulfuric acid, aerated	concentrated	boiling	212 (5.38)
Sodium citrate	saturated	room	nil	with air	1	212 (100)	282 (7.16)
Sodium cyanide	saturated	room	nil	Sulfuric acid, aerated	3	212 (100)	830 (21.1)
Sodium dichromate	saturated	room	nil	with nitrogen	5	212 (100)	1060 (26.9)
Sodium fluoride	saturated	room	0.3 (0.008)	Sulfuric acid	1	boiling	700 (17.8)
Sodium hydrosulfide + unknown amounts of sodium sulfide and polysulfides	5-12	230 (110)	<0.1 (<0.003)	Sulfuric acid	5	boiling	1000 (25.4)
Sodium hydroxide	5-10	70 (21)	0.04 (0.001)	+ 0.25% CuSO ₄	5	200 (93)	nil
Sodium hydroxide	10	boiling	0.84 (0.021)	+ 0.25% CuSO ₄	30	100 (38)	2.4 (0.061)
Sodium hydroxide	28	room	0.1 (0.003)	+ 0.25% CuSO ₄	30	200 (93)	3.48 (0.088)
Sodium hydroxide	40	176 (80)	5.0 (0.127)	+ 0.5% CuSO ₄	30	100 (38)	2.64 (0.067)
Sodium hydroxide	50	135 (57)	0.5 (0.0127)	+ 0.5% CuSO ₄	30	200 (93)	32.4 (0.823)
Sodium hydroxide	73	265 (129)	7.0 (0.178)	+ 1.0% CuSO ₄	30	100 (38)	0.78 (0.020)
Sodium hydroxide	50-73	370 (188)	>43 (>1.09)	+ 1.0% CuSO ₄	30	200 (93)	34.8 (0.884)
Sodium hypochlorite	6	room	nil	+ 0.5% CrO ₃	5	200 (93)	nil
Sodium hypochlorite + 12-15% NaCl + 1% NaOH + 1-2% sodium carbonate	1.5-4	150-200 (66-93)	1.2 (0.030)	+ 0.5% CrO ₃	30	200 (93)	65 (1.65)
Sodium nitrate	saturated	room	nil	+ 1.0% CuSO ₄	30	boiling	100 (38)
Sodium nitrite	saturated	room	nil	Sulfuric acid vapors	96	150 (66)	nil
Sodium perchlorate	900 g/l	122 (50)	0.1 (0.003)	Sulfuric acid vapors	96	200-300	0.4-0.5 (0.010-0.013)
Sodium phosphate	saturated	room	nil				
Sodium silicate	25	boiling	nil				
Sodium sulfate	10-20	boiling	nil				
Sodium sulfate	saturated	room	nil				
Sodium sulfide	10	boiling	1.08 (0.027)				
Sodium sulfide	saturated	room	nil				
Sodium sulfite	saturated	boiling	nil				
Sodium thiosulfate	25	boiling	nil				
Sodium thiosulfate + 20% acetic acid	20	room	nil				
Soils, corrosive	—	ambient	nil				
Stannic chloride	5	212 (100)	0.12 (0.003)				
Stannic chloride	24	boiling	1.76 (0.045)				
Stannic chloride, molten	100	150 (66)	nil				

Appendix

Titanium Corrosion Rate Data — *TIMETAL*® Commercially Pure Grades

These data were determined in laboratory tests and are intended only as a guide. Since service conditions may be dissimilar, *TIMET* recommends testing under the anticipated operating conditions.

C = Concentration %

T = Temperature °F (°C)

R = Corrosion rate, mpy (mm/y)

MEDIA	C	T	R
Sulfuric acid,		(93-149)	
+ 10% HNO ₃	90	room	18 (0.457)
+ 30% HNO ₃	70	room	25 (0.635)
+ 50% HNO ₃	50	room	25 (0.635)
+ 70% HNO ₃	30	room	4.0 (0.102)
+ 90% HNO ₃	10	room	nil
+ 90% HNO ₃	10	140 (60)	0.45 (0.011)
+ 50% HNO ₃	50	140 (60)	15.7 (0.399)
+ 20% HNO ₃	80	140 (60)	62.5 (1.59)
Sulfuric acid saturated	45	75 (24)	0.13 (0.003)
with chlorine			
Sulfuric acid saturated	62	60 (16)	0.07 (0.002)
with chlorine			
Sulfuric acid saturated	5	374 (190)	<1 (<0.025)
with chlorine			
Sulfuric acid saturated	82	122 (50)	>47 (>1.19)
with chlorine			
Sulfuric acid + 4.79	40	212 (100)	passive
g/l Ti + "			
Sulfurous acid	6	room	nil
Tannic acid	25	212 (100)	nil
Tartaric acid	10-50	212 (100)	<5 (<0.127)
Tartaric acid	10	140 (60)	0.10 (0.003)
Tartaric acid	25	140 (60)	0.10 (0.003)
Tartaric acid	50	140 (60)	0.02 (0.001)
Tartaric acid	10	212 (100)	0.13 (0.003)
Tartaric acid	25	212 (100)	nil
Tartaric acid	50	212 (100)	0.2-0.49 (0.005-0.0121)
Terephthalic acid	77	425 (218)	nil
Tetrachloroethane,	100	boiling	0.02 (0.001)
liquid and vapor			
Tetrachloroethylene	-	boiling	5 (0.127)
+ H ₂ O			
Tetrachloroethylene	100	boiling	nil
Tetrachloroethylene,	100	boiling	0.02 (0.001)
liquid and vapor			
stabilized with ethyl			
alcohol			
Tin, molten	100	930 (499)	resistant
Titanium tetrachloride	99.8	572 (300)	62 (1.57)
Titanium tetrachloride	concentrated	room	nil
Trichloroacetic acid	100	boiling	573 (14.6)
Trichloroethylene	99	boiling	0.1-5 (0.003-0.127)
Uranium chloride	saturated	70-194 (21-90)	nil
Uranyl ammonium	20.9	165	<0.1 (<0.003)
phosphate filtrate +			
25% chloride + 0.5%			
fluoride, 1.4%			
ammonia + 2.4%			
uranium			
Uranyl nitrate	120 g/l U	boiling	0.012 (0.000)
containing 25.3 g/l			
Fe ³⁺ , 6.9 g/l			
Cr ³⁺ , 2.8 g/l			
Ni ²⁺ , 5.9 molar NO ₃			
4.0 molar H ⁺ , 1.0			
molar Cl			
Uranyl sulfate + 3.1	3.1 molar	482 (250)	0-0.78 (<0.020)
molar Li ₂ SO ₄ +			
100-200 ppm O ₂			
Uranyl sulfate + 3.6	3.8 molar	662 (350)	0.22-17 (0.006-0.432)
molar Li ₂ SO ₄ , 50 psi O ₂			
Urea-ammonia	-	elevated	no attack
reaction mass		temp. and	
		pressure	
Urea + 32% ammonia,	28	360 (182)	3.1 (0.079)
+ 20.5% H ₂ O, 19% CO ₂			
Water, degassed	-	600 (316)	nil
Water, river, saturated	-	200 (93)	nil
with Cl ₂			
Water, synthetic sea	-	95 (35)	nil

MEDIA	C	T	R
X-ray developer solution	-	room	nil
Zinc, subjected to zinc	100	molten	withstood
ammonium chloride			several
reflux			thousand
			contact
			cycles
Zinc chloride	20	220 (104)	nil*
Zinc chloride	50	302 (150)	nil*
Zinc chloride	75	392 (200)	24 (0.610)*
Zinc chloride	80	392 (200)	8000 (203.2)*
Zinc sulfate	saturated	room	nil

Corrosion Rate Data for *TIMETAL*® 50A Pd

C = Concentration %

T = Temperature °F (°C)

R = Corrosion rate, mpy (mm/y)

MEDIA	C	T	R
Aluminum Chloride	10	212 (100)	<1 (<0.025)
	25	212 (100)	1 (0.025)
Calcium Chloride	62	310 (154)	nil
	73	350 (177)	nil
Chlorine, wet	-	room	slight gain
Chlorine, H ₂ O Sat'd.	-	room	<1 (<0.025)
Chromic acid	10	boiling	slight gain
Ferric chloride	30	boiling	slight gain
Formic acid	50	boiling	3 (0.076)
Hydrochloric acid,	1-15	room	<1 (<0.025)
H ₂ saturated	20	room	4 (0.102)
	25	room	11 (0.279)
	1	158 (70)	3 (0.076)
	5	158 (70)	3 (0.076)
	10	158 (70)	7 (0.178)
	15	158 (70)	13 (0.330)
	20	158 (70)	61 (1.55)
	25	158 (70)	169 (4.29)
	3	374 (190)	1 (0.025)
	5	374 (190)	4 (0.102)
	10	374 (190)	350 (8.89)
	15	374 (190)	1620 (41.1)
Hydrochloric acid,	1 and 5	158 (70)	<1 (<0.025)
Air saturated	10	158 (70)	2 (0.050)
	15	158 (70)	6 (0.152)
	20	158 (70)	26 (0.660)
	25	158 (70)	78 (1.98)
Hydrochloric acid,	3	374 (190)	5 (0.127)
O ₂ saturated	5	374 (190)	5 (0.127)
	10	374 (190)	368 (9.34)
Hydrochloric acid,	3 and 5	374 (190)	<1 (<0.025)
Cl ₂ saturated	10	374 (190)	1140 (29.0)
Hydrochloric acid	5	boiling	7 (0.178)
	10	boiling	32 (0.813)
	15	boiling	267 (6.78)
	20	boiling	770 (19.6)
Hydrochloric acid			
+ 5 g/l FeCl ₃	10	boiling	11 (0.279)
+ 16 g/l FeCl ₃	10	boiling	3 (0.076)
+ 16 g/l FeCl ₃	20	boiling	113 (2.87)
+ 16 g/l CuCl ₂	10	boiling	5 (0.127)
+ 16 g/l CuCl ₂	20	boiling	146 (3.71)
Nitric acid	30	374 (190)	94 (2.39)
	30	482 (250)	slight gain
	65	boiling	28 (0.65)
	65	374 (190)	slight gain
	65	482 (250)	slight gain
Nitric acid,			
Unbleached	60	boiling	15.5 (0.394)
Phosphoric acid	10	boiling	5.8 (0.147)
Sodium chloride			

* May corrode in crevices

Appendix

Titanium Corrosion Rate Data — *TIMETAL*® Commercially Pure Grades

These data were determined in laboratory tests and are intended only as a guide. Since service conditions may be dissimilar, *TIMET* recommends testing under the anticipated operating conditions.

C = Concentration %

T = Temperature F (C)

R = Corrosion rate, mpy (mm y)

MEDIA	C	T	R
Brine	—	200 (93)	0.0005 (0.000)
Sodium chloride	10	374 (190)	<1 (<0.025)
Sulfuric acid	5	room	<1 (<0.025)
N ₂ saturated	10	room	1 (0.025)
	40	room	9 (0.229)
	60	room	34 (0.864)
	80	room	645 (16.4)
	95	room	68 (1.73)
Sulfuric acid	5	158 (70)	6 (0.152)
N ₂ saturated	10	158 (70)	10 (0.254)
	40	158 (70)	87 (2.21)
	60	158 (70)	184 (4.67)
	80	158 (70)	226 (5.74)
	96	158 (70)	62 (1.57)
	1	374 (190)	5 (0.127)
	5	374 (190)	5 (0.127)
	10	374 (190)	59 (1.50)
	20	374 (190)	355 (9.02)
Sulfuric acid	1	374 (190)	5 (0.127)
O ₂ saturated	5	374 (190)	3 (0.076)
	10	374 (190)	5 (0.127)
	20	374 (190)	59 (1.50)
	30	374 (190)	2440 (62.0)
Sulfuric acid	1 and 5	374 (190)	<1 (<0.025)
Cl ₂ saturated	10	374 (190)	2 (0.05)
	20	374 (190)	15 (0.38)
	30	374 (190)	3060 (77.7)

MEDIA	C	T	R
Sulfuric acid	5	158 (70)	3 (0.08)
Air saturated	10	158 (70)	4 (0.10)
	40	158 (70)	37 (0.94)
	60	158 (70)	392 (10.0)
	80	158 (70)	447 (11.4)
	96	158 (70)	83 (2.1)
Sulfuric acid	5	boiling	20 (0.05)
	10	boiling	59 (1.5)
	20	boiling	207 (5.3)
Sulfuric acid			
+ 0.5 g/l Fe ₂ (SO ₄) ₃	10	boiling	7 (0.18)
+ 16 g/l Fe ₂ (SO ₄) ₃	10	boiling	<1 (<0.025)
+ 16 g/l Fe ₂ (SO ₄) ₃	20	boiling	6 (0.15)
+ 40 g/l Fe ₂ (SO ₄) ₃	40	boiling	87 (2.2)
Sulfuric acid			
+ 15% CuSO ₄	15	boiling	25 (0.64)
Sulfuric acid			
+ 10% FeSO ₄			
11% Solids, and			
170 g/l TiO ₂	23	to 212 (100)	84 (2.13)
Sulfuric acid			
+ 0.01% CuSO ₄	30	boiling	1090 (27.7)
+ 0.05% CuSO ₄	30	boiling	1310 (33.3)
+ 0.50% CuSO ₄	30	boiling	79 (2.01)
+ 1.0% CuSO ₄	30	boiling	69 (1.75)

Corrosion Rate Data for *TIMETAL*® Code-12

C = Concentration %

T = Temperature F (C)

R = Corrosion rate, mpy (mm y)

MEDIA	C	T	R	Remarks
Ammonium hydroxide	30	boiling	nil	no hydrogen pick-up
Aluminum Chloride	10	boiling	nil	500 hours
Aqua regia	(1 part HNO ₃ + 3 parts HCl)	boiling	24 (0.610)	
Ammonium Chloride	10	boiling	nil	500 hours
Chlorine cell	—	190 (88)	.035 (0.001)	3700 hours
off-gas	—	boiling	0.5 (0.013)	
Citric acid	50	boiling	nil	natural aeration
Formic acid	45	boiling	nil	natural aeration
Formic acid	88	boiling	nil	natural aeration
Formic acid	90	boiling	20.5 (0.521)	natural aeration
Hydrochloric acid	5	120 (49)	0.1 (0.003)	
Hydrochloric acid	5	150 (66)	0.2 (0.005)	
Hydrochloric acid	5	200 (93)	1176 (29.9)	
Hydrochloric acid	2	200 (93)	1.2 (0.031)	
HCl + 2g/l FeCl ₃	3.32	196 (91)	1.0 (0.025)	
HCl + 2g/l FeCl ₃	4.15	196 (91)	2.3 (0.058)	
Sulfuric acid	0.54	boiling	0.6 (0.015)	
Sulfuric acid	1.08	boiling	35.4 (0.899)	
Sulfuric acid	1.62	boiling	578 (14.7)	
Vapor above boiling				
HNO ₃	—	—	0.8 (0.020)	
MgCl ₂	saturated	boiling	nil	500 hours
Sodium Sulfate	10	boiling	nil	acidified to pH 1
5% NaOCl + 2% NaCl + 4% NaOH	—	boiling	2.4 (0.061)	500 hours
NaCl	saturated	600 (316)	nil	500 hours